CAN AGRICULTURAL INTENSIFICATION EXPLAIN UNEXPECTED COOLING OF EXTREME HEAT IN THE MIDWESTERN UNITED STATES?

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I certify that I have read this thesis and that, in my opinion, it is satisfactory in scope and quality as a thesis for the degree of Bachelor of Science in Global Environmental Science.

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ABSTRACT

Despite climate change, data show decreasing maximum temperatures in a portion of the midwestern United States during the mid-summer. The cause of this "warming hole" is unknown. Previous research has discussed the importance of aerosols, atmospheric circulation, and agriculture as contributors to this phenomenon. In this research I examine the effect of corn and soybean production, the two most prevalent crops in the Midwest, on maximum temperature anomalies during the summer. I develop a novel test of the hypothesis, motivated by the research of Mueller et al. (2016), that the unusual cooling is a result of changes in agriculture via the biological process of evapotranspiration. Specifically, using data on crop progress from 1981 to 2019, I compare year-to-year variability in timing of peak transpiration to the corresponding temperature anomalies. I find mixed results. Soybeans seem to have a cooling effect on the maximum temperatures while corn seems to have a warming effect. This challenges what one would assume from the literature that corn, which has a slightly greater evapotranspiration rate, should have greater or similar cooling effects as soybeans. These findings suggest that while agricultural activity may influence the climate, the link is more complex than simple evapotranspirative cooling. While the mechanism is not clear, the empirical evidence suggests that growth of soybean production may have contributed to the Midwestern warming hole.

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1.0 INTRODUCTION

Global warming is affecting communities across the planet. It is predicted that the world will warm at least 2°C on average since the benchmark set around 1800 (Sherwood et al., 2020). One area that may be particularly susceptible to climate change is agriculture in the midwestern region of the United States, a region that is critical to world food commodity prices and food systems globally. This region produces approximately 40 percent of the world's corn and soybeans, and nearly a quarter of the world's caloric basis of food production. Earlier research indicates that climate change could increase the frequency of extreme heat and associated drought in this region, causing up to an 80 percent decline in output by the end of the century (Schlenker & Roberts, 2009). Contrary to this prediction, however, weather during the summer months has been relatively more temperate than history, not more extreme, and there is no indication yet that changing weather patterns are severely impacting production of these crops. In fact, the data show that average summertime temperatures have decreased in the Midwest where these crops are most prevalent. The exact cause of this "warming hole" is unknown. Previous research suggests the possible role of aerosols, atmospheric circulation, and agriculture (Partridge et al., 2018; Alter et al., 2018). The goal of this research project is to examine whether agricultural production may be acting to moderate extreme heat and thereby contributing to the warming hole of the Midwestern United States using historical data. We will test the hypothesis, motivated by the research of Mueller et al., that the unusual cooling is a result of changes in agriculture via the biological process of evapotranspiration (2016). By analyzing corn and soybean during its peak evapotranspiration periods for each of the corn belt states against maximum temperature anomalies, we aim to strengthen the hypothesis by utilizing analysis not based on general linear trends.

1.1 Agricultural role in the 21st century and beyond

The agricultural system has grown to depend on and support other large industries such as transportation and international policy. In the United States, farming directly provides 2.6 million jobs and is the backbone of 391 rural county economies (United States Department of Agriculture [USDA], 2020). On a global scale, one of the most significant agricultural issues to address in the near future is the plan to properly feed over 9 billion people by 2050 without expanding existing agricultural lands (Miller, 2016). The resolution requires an interdisciplinary policy change heavily rooted in science (Miller, 2016). Agriculture today is already very evolved from what it was a century ago, for example, in the intensification of croplands with the introduction of a dedicated seed industry, commercial fertilizer, pesticides, biotechnology, and heavy machinery.

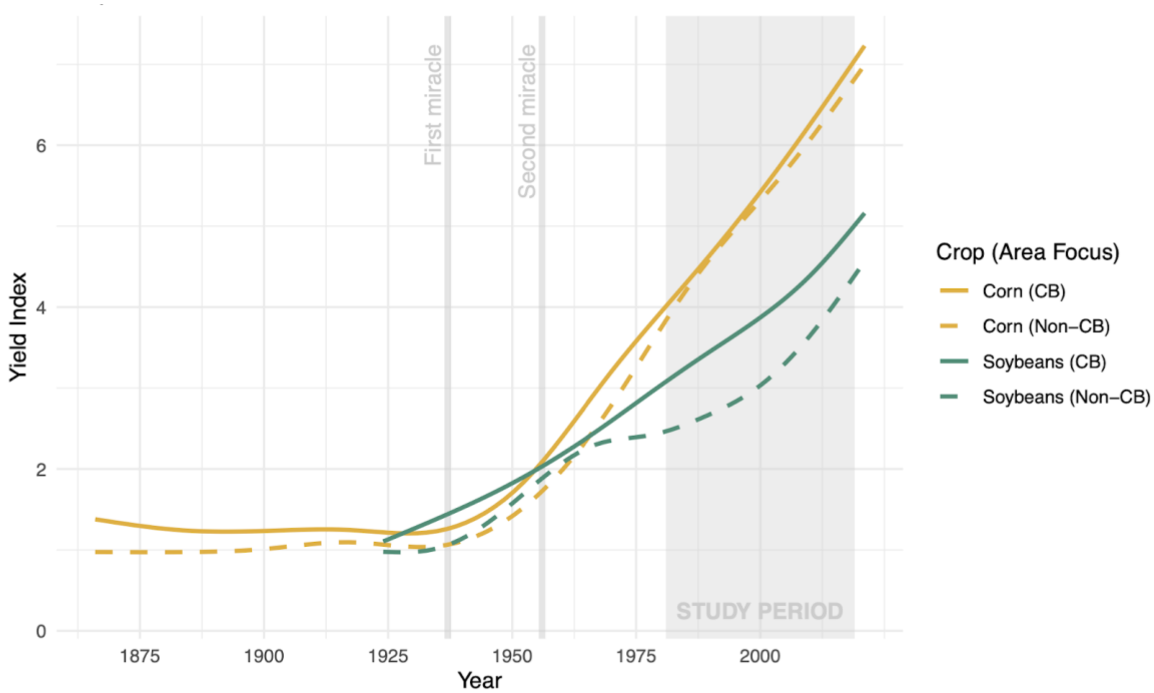
Leading up to and after the time of the Green Revolution in the 1960s, intense agricultural research has led to efficient planting of major staple crops (USDA, 2003). The commonly used diverse farming approach of pre-mid-20th century was traded for monocropping or specialized planting and greater profits of cash crops (Hart, 2003). By 1997, most of the Midwestern heartland counties increased their farms' share of crop sales by more than five percentage points from 1949 (Hart, 2003). Hart (2003) attributes this increase to a shift from a mixed crop-and-livestock rotation to strictly growing corn and soybeans. Hybrid corn varieties had become available in 1933 and continually developed, improving pest resistance and doubling or tripling field yields (Hart, 2003). In 2000, a third of corn and half of soybeans seeds were genetically modified (Hart, 2003).

Machinery and other cropping practices were simultaneously upgraded as well, including the use of cylindrical grain storage and harvest machines (Hart, 2003). The result is a more concentrated agricultural production, where by 1997, 4% of farms produced 57% of farm products (Hart, 2003).

Hybrid corn adoption was logistic with a moving ceiling, as Griliches defined in his 1957 landmark paper and 1980 response (Griliches, 1957; Griliches, 1980). As hybrid agriculture is a technological innovation method, it is continually improved and we see improvements in innovation to this day (Griliches, 1957; Nielsen, 2021). As nearly all corn in the US is now hybrid, improvements in hybrid technology are clearly seen in the improvements of corn yield (Figure 1). There is a noticeable difference in corn belt and non-corn belt yields especially during the early period of hybrid corn adoption, explainable by Griliches' observations that hybrid corn adoption was quicker in areas where profitability was greater, or where there was greater corn cultivation (1957). Seed companies sending salesmen directly to farmers within the corn belt region, hence providing more accessibility to these new hybrid seeds, as opposed to the south, where farmers purchased seeds on their own (Griliches, 1957). Soybean hybrids are difficult to produce due to pollination issues and hence have not been widely released in the commercial market (Tew, 2008). Other general efficiency improvements in agricultural practices such as herbicides in addition to the introduction of biotechnology in the more recent years have also positively impacted yield ratios for both crop types.

Figure 1

Crop Yield for Corn Belt (CB) and Non-Corn Belt (Non-CB) regions



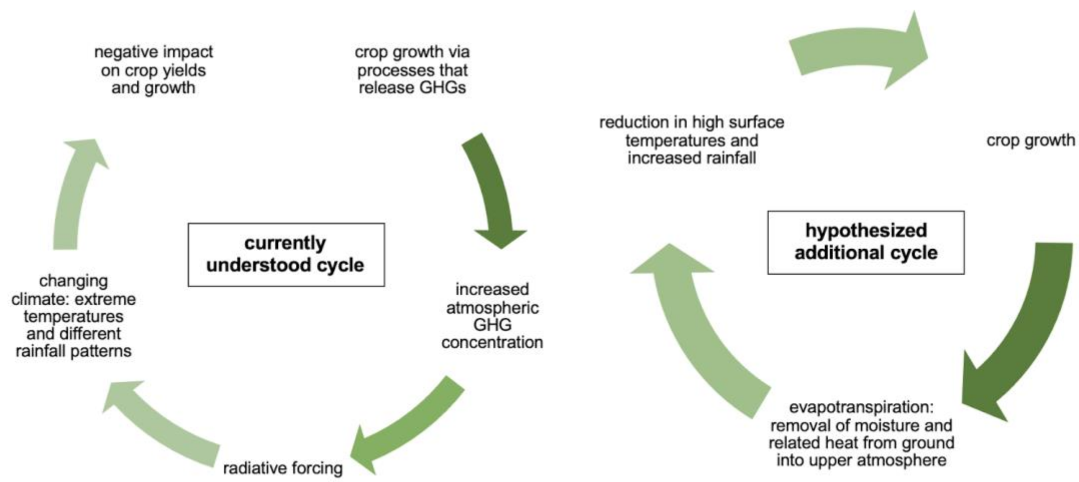
Note: Smoothed lines of trends in a yield index for corn grain (yellow) and soybean (green), with solid lines representing states within the corn belt region (CB) and dotted lines representing states outside of the corn belt region (Non-CB). The yield is indexed to the yield of corn or soybeans in 1924, which was the first year of available data for soybeans from the USDA and before large adoption of corn hybrids in the late 1930s and 40s. Lines defining the first "miracle" and second "miracle" in corn hybrid technological advances, as defined by Nielson (2021) are marked on the plot. Study period of this paper (1981 - 2019), which is within the period of increased yields, is also shaded. State level data obtained from USDA NASS for all available years for all available states.

So while the total cropland, which includes land used for crops for harvest, pasture, and idly, in the United States is ever so slightly decreasing and the number of farms has dramatically dropped from its 1930s high, the average farm acreage and the total factor productivity has greatly increased (USDA, 2019a; USDA, 2019b; USDA, 2020). A study looking at cropland conversion rates within 3 km grids during the 2008-2016 time period found that areas in the Midwest were generally expanding in cropland area while other parts of the United States saw cropland abandonment (Lark et al., 2020). Additionally, Lark et al. conclude that these new croplands were generally less-suited for crops in relation to nearby existing cropland as seen in lower yield rates (2020). The conversion of wild areas to agricultural land raises concerns of habitat removal and a decreasing regional biodiversity (Lark et al., 2020).

Intensification of agricultural lands raises many downstream environmental concerns beyond the initial trade-offs of land use conversion, including erosion, eutrophication, stripping of soils of essential nutrients, and unintended biological impacts stemming from pest control and mineral fertilizers. Agricultural- and food-related systems also generate a significant level of greenhouse gases; notably, CO_2 is released from fossil fuels utilized in transportation, water pumps for irrigation, and production of chemical fertilizers. In addition to radiative forcing concerns of greenhouse gas emissions, acidification of the environment is also an issue that affects crop growth (Weidema, 2019, p. 18). If the hypothesis that temperatures may cool as a result of crop evapotranspiration is proven, agriculture would seemingly have a negative (or enforcing) feedback loop of crop growth alongside the obvious positive (or open) feedback loop of a warming planet via greenhouse gas outputs, radiative forcing, and stunted crop growth (Figure 2). Water use is also a major concern in agriculture, as 80–90% of human freshwater consumption is in this sector (Weidema, 2019, p. 154). Alongside freshwater scarcity, salination, and water pollution, the process tested in the hypothesis, evapotranspiration, is an important issue to consider regarding crop water footprint (Weidema, 2019, pp. 160-162).

Figure 2

Cycles of Currently Understood and Hypothesized Impact of Crop Growth on Climate and Its Impact on Crop Growth



1.2 The warming hole

Despite the global trend towards a warming climate, the Midwestern United States has noticed a surprising decrease in high temperatures during the summer season. There is some discrepancy in establishing the border, seasonality, and start of this "warming hole" due to differences in temperature data sources, time periods studied, and interpretation of anomaly; however, it is generally agreed that there is a lack of global-warming-effect in the Midwest. Existence of the unexpected warming hole is supported by various climate models that are unable to report accurate results in the Midwest, particularly during the summer time (Winter et al., 2015; Pan et al., 2004). Winter et al. (2015) attempted to utilize climate modeling to explain trends in hydrology, including soil moisture levels, in Illinois and found the results to be insignificant, further confirming the inaccuracies of climate models in this region and that this area does not seem sensitive to global warming.

Different datasets on historical temperatures also generate different results, with some claiming the warming hole to be further south or towards the great plains with slightly different trends for seasons. Discrepancies occur between and even among reanalysis datasets and interpolation station datasets (Grotjahn & Huynh, 2018). Partridge et al. (2018) attempted to establish the warming hole boundary by using a pseudo-average temperature $\frac{T_{max} - T_{min}}{2}$, observing a distinct shift in location of the warming hole from the Southeast during winter and spring, to the Midwest during summer and fall using Global Historical Climate Network data. They presented a simple approach to establishing a definition of cooling: by subtracting a 1901–2015 baseline mean from the daily observed temperatures during that time period (Partridge et al., 2018). Other methods of identifying the warming hole include utilizing the decadal trend for quantile analysis, comparing maximum temperature trends across varying lengths of years from a recent year, and comparing more recent temperatures to an earlier baseline period, just to name a few (Mueller et al., 2016; Portman et al., 2009; Grotjahn & Huynh, 2018; Robinson et al., 2002).

The cause of the warming hole has been unexplainable in its entirety. Anthropogenic and biogenic aerosols, which have been established to cause cooling when air moisture allows, have been found to possibly have an effect or conjunctural effect on the warming hole (Banrjee et al., 2017; Yu et al., 2014; Mascioli et al., 2017). The mechanism by which aerosols cool is its potential to be cloud condensation nuclei or ice nuclei, which are key in cloud formation and hence, indirectly, albedo (Yu et al., 2014). Cooling has also been attributed to changes in the low-level jet-stream, causing moisture convergence and increased precipitation, which increases cloud shading and soil moisture, which increases evapotranspiration (Pan et al., 2004). However, Pan et al.'s (2014) warming hole location appears more central in the United States, rather than midwestern or northcentral. By the similar mechanism of evapotranspiration, agricultural intensification has been identified as a possible driver of the warming hole (Mueller et al., 2016; Nikiel & Eltahir, 2019). These claims motivate our hypothesis which aims to test these claims once again.

Sea surface temperature of the Pacific and Atlantic ocean and ocean-atmospheric circulation have also been referred to as a forcing factor, or at the least, contributor to increased precipitation (Partridge et al. 2018; Grotjahn & Huynh, 2018). Kumar et al. (2013) utilized climate modeling and found the North Atlantic multidecadal oscillation to be one driver of the warming hole. Meehl et al. (2012) explored the possible effects of Interdecadal Pacific Oscillation (IPO) decadal variability, finding a strong negative correlation, without throwing out the possibility of enforcement by North Atlantic sea surface temperatures. However, in later studies, Meehl et al. (2015) observed a reversal of the warming hole beginning the early 2000s, claiming that it was associated with the IPO transitioning to a negative phase. This contrasts with other studies which claim that the warming hole is still present, and hence, we once re-emphasize the difference in studies depending on dataset used and anomaly or trend definition (Partridge et al., 2018; Mueller et al., 2016). It is undeniable, though, that at some point in time, the Midwest has experienced some level of cooling or lack of heating, on top of a long-term increasing precipitation trend.

Grotjahn and Huynh found that including the increasing air moisture in the Midwestern warming hole increased the heat stress and temperature-humidity index, hence impacting human and animal discomfort and mortality unfavorably (Grotjahn & Huynh, 2018). While the addition of increased air moisture does not have a positive effect on humans and animals, an increased precipitation, representative of moisture convergence in the midwestern region, have been shown to reduce the negative effects of extreme high temperatures on crop such as corn (Lobell et al., 2013; Schlenker & Roberts, 2009).

1.3 Previous literature on agricultural impacts on the warming hole

Presently, notable studies linking agricultural activity and the presence of a warming hole analyze linear temperature trends and linear agricultural trends in the cooling area across years (Mueller et al., 2016; Nikiel & Eltahir, 2019). But this hypothesis could be better supported by a study that was less focused on general linear trends, hence the basis of this study.

In 2016, Mueller et al. presented their findings that agriculture, particularly areas that were irrigated, could be a possible driver of the warming hole. They analyzed decadal trends of net primary productivity, irrigation, and crop area conversion against a trend of the 95th percentile of daily maximum temperature trends during the summer (Mueller et al., 2016). Global Historical Climatology Network (GHCN) was used as the weather dataset. Acknowledging that lower percentiles (such as the 5th percentile) of maximum temperature trends during the summer did not display strong support for the warming hole, they chose to exclude other percentiles from further analysis (Mueller et al., 2016).

Studies in the past have also acknowledged the stronger presence of the warming hole when only analyzing higher percentiles (Portmann et al., 2009). In a later study, Mueller et al. (2017) used a similar method for analysis for other areas of the globe which display less high temperatures and intense agriculture as well, and found similar results where irrigation and intensification of crop show significant relationship to 95th percentile maximum temperatures during the summer, but crop area trends fail to show significance. A possible explanation for the lack of significance in the rate of cropland conversion and the temperature trends is that the land that is converted into cropland could possibly have similar or even greater levels of evapotranspiration. Baeumler et al. (2019) and Garcia y Garcia and Strock (2018), among others, have compared total evapotranspiration of prairie grass to that of corn and soy, finding that prairie grass has similar annual evapotranspiration.

Nikiel and Eltahir (2019) took a more holistic approach, analyzing the combined effects of cropland conversion, intensification, and irrigation, in addition to sea surface temperature and greenhouse gas trends. They model the effect of different scenarios using the MIT Regional Climate Model and consider the differences of simulations. They also compare the modeled results to observed evapotranspiration, average temperature, and precipitation from a reanalysis weather dataset called Climatic Research Unit (Nikiel & Eltahir, 2019).

1.4 Evapotranspiration and growth of corn and soybean crops

Evapotranspiration is a process in the water cycle that transports water and its related energy from the soil to the upper atmosphere (United States Geological Survey [USGS], n.d.a). Total evapotranspiration includes evaporation directly from the surface of water bodies and soil and transpiration from plants (USGS, n.d.a). Transpiration is the process whereby the plant absorbs water through roots, through the rest of the plant due to adhesion and cohesion of water molecules, and releases the water through evaporation via open stomata (Verstraeten et al., 2008). Water in its liquid phase is transformed to vapor after energy is applied to the water molecules, enough to reach its latent heat of vaporization. Hence, this process removes heat from the surface of the earth. While evapotranspiration is made of bio-physical transpiration and physical evaporation, these components are not easily separately quantified and hence various attempts have been made to approximate true evapotranspiration of major crops types under different conditions to this day (Verstraeten et al., 2008; Baeumler et al., 2019). Biotic factors, such as type of vegetation, and abiotic factors, such as temperature, relative humidity, wind, and soil moisture, all affect evapotranspiration rates (USGS, n.d.a).

Temperature or solar radiation affect rates of evaporation simply due to the physics of phase changes, laws of equilibrium fuel the change in evapotranspiration via atmospheric relative humidity and magnitude of wind which moves away saturated air (USGS, n.d.a). Additionally, soil moisture affects evapotranspiration rates simply because it is the source of water to be released (USGS, n.d.a). As evapotranspiration is the product of available water and energy, it plays an important part in water and energy cycles, and can be used to understand local weather cycles (Verstraeten et al., 2008). Current methods to evaluate the amount of evapotranspiration include controlled experiments measuring soil moisture, calculations utilizing previously established coefficients specific to crop type, bagging of crop, and utilizing modeling techniques to account for weather observations and various other factors simultaneously (USGS, n.d.a; Baeumler, et al. 2019; Verstraeten et al., 2008).

Plants with a more extensive root network have the possibility of absorbing relatively more water from the soil, and plants with larger leaf area or higher stomatal conductance have the possibility of releasing relatively more water into the atmosphere (Schlesinger & Bernhardt, 2013; Ma et al., 2010). It should be noted that corn, a C4 plant has a higher water use efficiency, or crop-matter-to-transpiration ratio, than soybean which is a C3 plant, as it is able to close stomata during the day time to avoid transpiration (Verstraeten et al., 2008). However, corn is a larger plant, with larger leaves and root length density than that of soybean, and hence, a more evapotranspiration is expected and observed to be greater than that of soybeans (Baeumler, et al. 2019; Garcia y Garcia & Strock, 2018). The greater total water demand of corn is also well documented in recommendations on crop irrigation (USDA, 2005).

Within the corn cultivation period, the highest rate of observed evapotranspiration has been established as the VT and R1 period, called tassel emergence/tasseling and pollination/silking (Kelley, 2016; Lauer, 2021). The exact number of days corn needs to reach these growth stages is unknown, as it varies based on corn type, temperatures of the season, and location. Corn growth stage can be more accurately predicted using the measurement of cumulative growing degree days (GDD), or the cumulative sum of temperatures above the 29°C threshold from date of planting (Schlenker & Roberts, 2009). If the average temperatures of the day, commonly calculated as $\frac{T_{max}- T_{min}}{2}$, are below the threshold temperature, the day contributes 0 growing degree units (GDU). Different types of corn have slightly different GDU requirements to reach each stage of growth. This metric is a well established standard in the agricultural community (Schlenker & Roberts, 2009). Hence, it is difficult to define a time period where corn crops have the most evapotranspiration, without considering the location and measured temperatures for the season. It is difficult to approximate a period of peak evapotranspiration for soybeans across all locations and years as well, for the same reasons. Peak evapotranspiration times for soybeans have been found to be around the R3 to R5 period, or beginning pod/setting pod/early podding and beginning seed (Anapalli et al., 2018; Karam et al., 2005)

2.0 DATA & METHODS

To test the hypothesis while avoiding the analysis of linear trends, the shift in crop planting times, which do not follow a clear linear trend across years, were analyzed against maximum temperature anomalies. All analysis, maps, and plots were generated using the R programming language in RStudio, and scripts will be made available on Github.

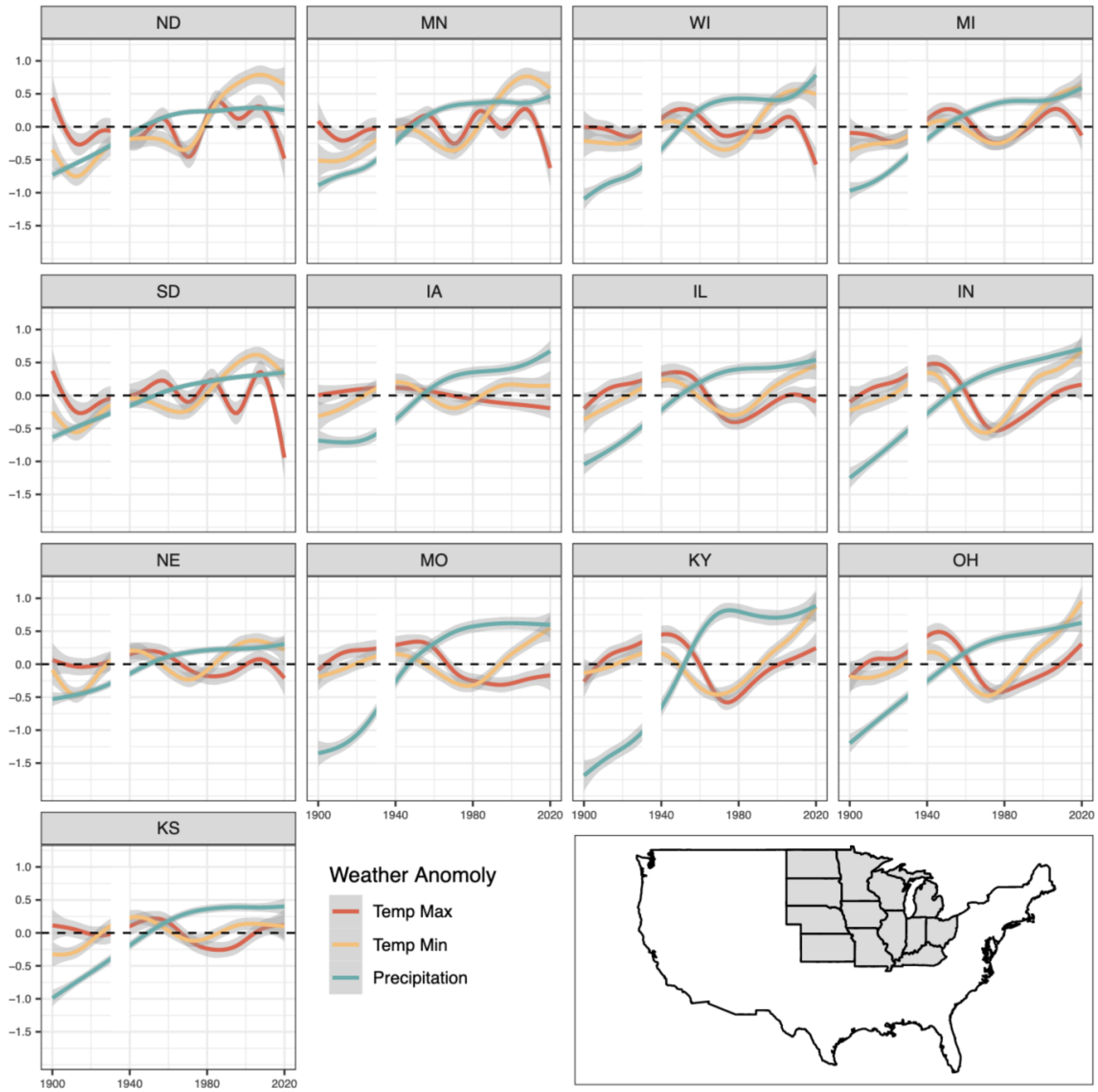
2.1 Weather data source

Weather data used was gridded daily maximum and minimum temperature and precipitation compiled and released by Wolfram Schlenker at Columbia University. This dataset has a similar structure to the PRISM weather dataset, however, a consistent set of weather station locations are used and missing data is filled using distance-weighted averages of other nearby stations (Schlenker, 2020). Temperature and precipitation anomalies were calculated by subtracting the values of each grid by the mean value of that grid for that day of the year across 110 years (1900–2019, excluding 1930–1939). This simple method of anomaly measurement was also used by Partridge et al. (2018). Benefits of using this method of calculating temperature anomalies, in comparison with linear changes in temperature were discussed by Partridge et al. (2018), citing an avoidance of issues regarding the differences in trends depending on the start and end year that Mascioli et al. (2017) and others observe in their analysis.

Weather in the 1930s, particularly in the Midwest, might have been affected by the Dust Bowl, and hence were not included to avoid bias in the mean. Partridge et al. found no significant difference between including and excluding Dust Bowl weather from 1936–1940 in their work on spatially defining the warming hole (2018). On the other hand, Mueller et al. found robustness in their model when excluding the 1930s Dust Bowl in addition to a maximum aerosol-induced cooling period from 1970s to 1990s (2016). However, 1970s–1990s is a very large exclusion of weather data, especially near our study period of 1981–2019; additionally, many have also cited a period of aerosol-induced cooling up to the mid-1970s potentially beginning in the 1950s, so we decided to include these time period in our calculation of means (Banerjee et al., 2017; Pan et al., 2004). By using this definition of temperature anomaly, we are able to achieve a normalization of the temperatures, so that anomalies can be compared with a decreased location or seasonality bias, with this simple linear shift, or centering (Figure 3). This also allows for a simple explanation of the results.

Figure 3

Smoothed Trend of Weather Anomalies from 1900–2019 Aggregated at the State Level for the Corn Belt Region



Note. Anomalies for maximum temperatures (red), minimum temperatures (light orange), and precipitation (teal) are calculated on a daily basis by subtracting the value from the mean over 110 years, so that a sum of all anomalies for each grid and day of the year is equal to 0. Values are then aggregated from grid level to state level. Data from 1930–

1939 (decade of the Dust Bowl) are excluded. Panels are arranged in relative location of each state, bottom left panel visually identifies the location of the corn belt states. It might be worth noting that the potentially aerosol-enforced cooling period of 1951–1975 studied by Banerjee et al. (2017) and Pan et al. (2004) are especially clearly seen in IL, IN, KY, and OH after smoothing the temperature data.

2.2 Crop growth season data source

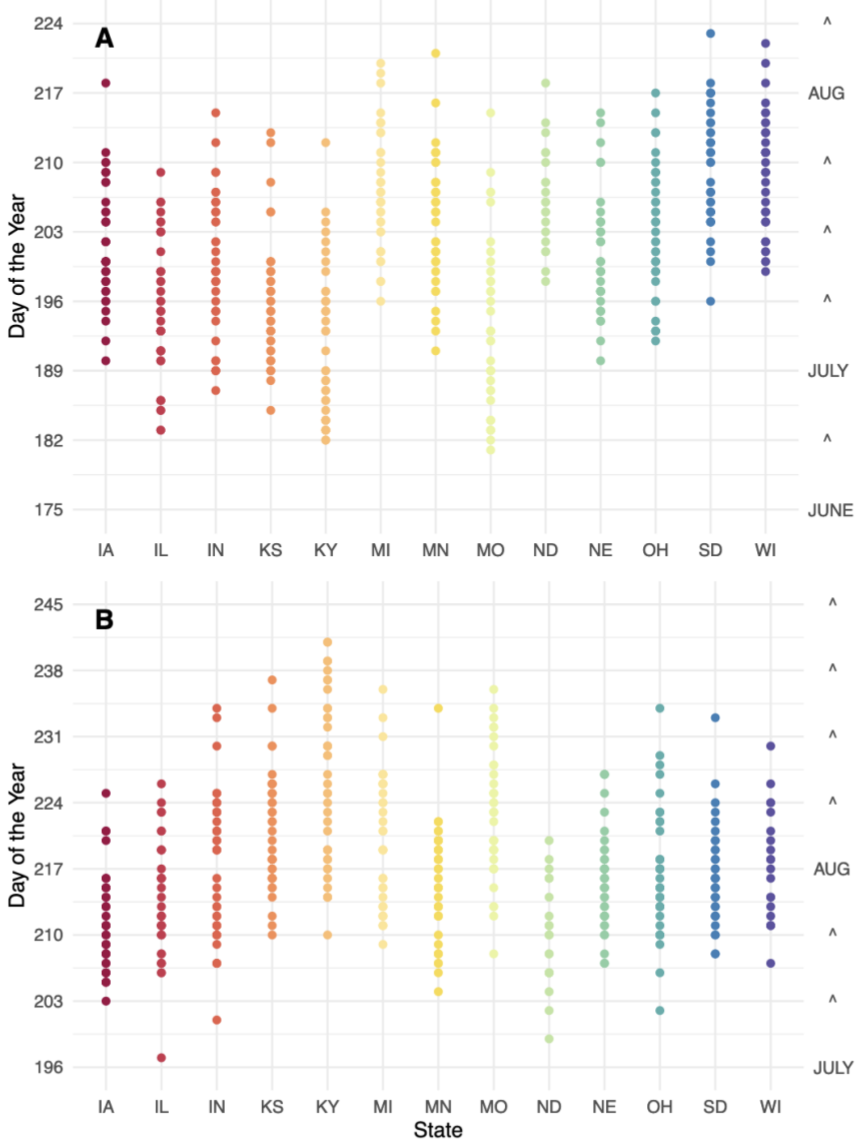
Crop growth data was obtained from the USDA National Agricultural Statistics Service (NASS) database, Quick Stats, via an API. The USDA releases weekly crop progress reports, which estimate the percentage of crop within the state are at or have passed certain growth stages for select states, including all 13 corn-belt states studied in this paper (Illinois, Indiana, Iowa, Kansas, Kentucky, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota, and Wisconsin). All years of available data until 2019 for the peak evapotranspiration growth periods for corn and soybean were included in the analysis (earliest data was from 1981).

In literature, the corn peak evapotranspiration period was established to be around the R1 growth stage, with some literature including the nearby VT and R2 periods as well. Corn silking (R1) weekly progress was linearly interpolated to daily percentage values of crop that have reached or passed R1. The day of the year that reaches the 50% value is identified and established as the fourth day of the "crop peak week-0" regardless of the day of the week (Figure 4). Every seven days before or after the beginning or end of the "crop peak week-0" are labeled as "crop peak week-n" where n is the count of "weeks" away from "crop peak week-0" up to 10 "weeks" before or after "crop peak week-0". This can be mathematically calculated for each day of the year (doy) as $n =$

$round((doy - doy_{50})\frac{1}{7})$ where $-10 \leq n \leq 10$ and is an integer and where $doy_{50}$is the day of the year at which half of the crop within the state has reached or passed the R1 stage.

Figure 4

Estimated Day of the Year Where the Corn (A) or Soybean (B) Crop have Reached or Passed the Peak Evapotranspiration Period Per Corn Belt State, 1981–2019



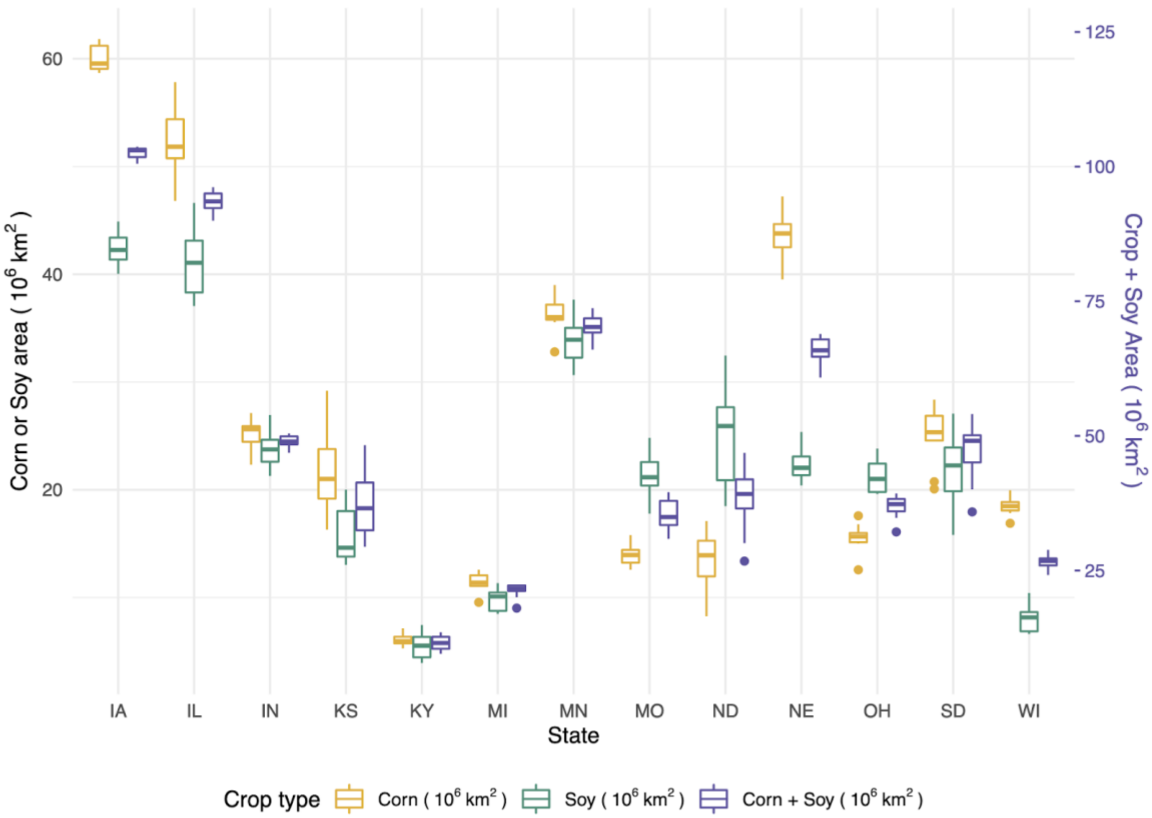
Note. Peak evapotranspiration period is silking and early podding, for corn and soybean respectively. Data for some years are missing in some states. Right-side markings indicate the approximate month each day of the year belongs to.

2.3 Crop area data source

The USDA NASS releases yearly data on cropland classification by analyzing satellite imagery in the cropland data layer (CDL). This data, released at a 30-meter resolution since 2010, was aggregated to the resolution of the gridded temperature data (2.5 x 2.5 mi) for the years 2010–2019 by Michael Roberts at the University of Hawai‘i (USGS, n.d.b.; Johnson & Mueller, 2010). At a state level of aggregation, crop area changes a relatively small percentage in relation to the total area of the state. Within the nine years of data Illinois saw the greatest decrease in the state’s land devoted to corn cultivation, at 6.7% (2011 to 2019), while soybean crop area increased. North Dakota saw the greatest increase in the state’s land devoted to soybean cultivation, at 6.9% (2010 to 2017), while corn crop area increased as well. Hence, changes in crop area were not included in the analysis, and an average across the nine years of data was used to represent crop area of respective grids and states. Nikiel and Eltahir (2019) established in their study that a majority of changes in cropland distribution occurred before 1940, which is before our study period. Additionally, Mueller et al. (2016) found crop area trends to have an insignificant effect on the warming hole. The limited change in absolute crop area can be seen in Figure 5.

Figure 5

Crop Areas for Corn and Soybean Within Each Corn Belt State, 2010–2019



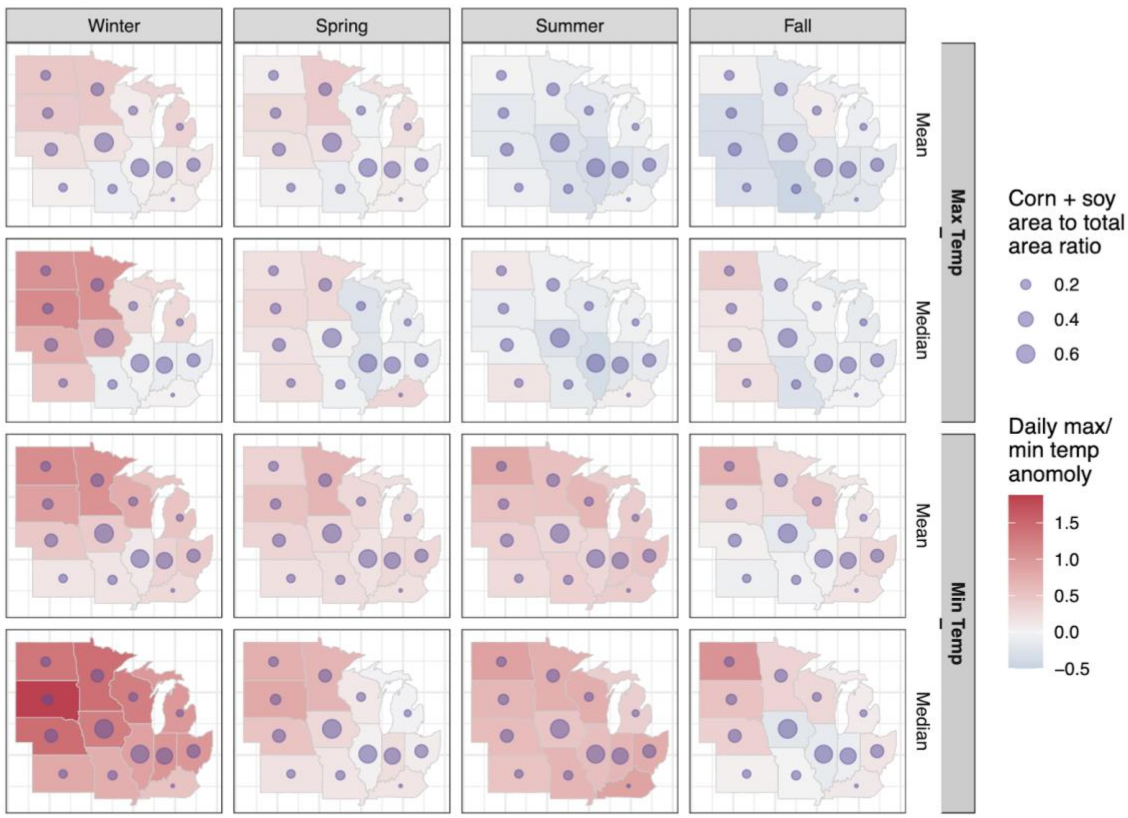
Note. Data shows the range of approximate amounts of total area of corn (yellow), soybean (green), and corn + soybean (indigo) cultivation between 2010 and 2019. Corn area and soybean area follow the left axis while corn + soybean area follow the right axis (indigo), which is scaled by two. Units are in million km^2.

2.4 Establishing validity in the temperature anomaly definition

Studies in the past have defined the warming hole by different definitions and as result have had mixed definitions of the location and boundary of this phenomenon. However, for simplicity purposes, we have decided to define temperature anomaly with an approach similar to that of Partridge et al. (2018), except utilizing only daily T_{max}, rather than daily $\frac{T_{max} - T_{min}}{2}$. To establish the validity of this method, we must observe the "warming hole" trend of decreasing maximum temperatures during the summer season within the warming hole. An analysis of the observed temperature anomaly during our relevant study period 1981–2019 shows that mean and median daily maximum temperature anomalies aggregated to the state level, are in fact, generally slightly negative during the summer (Figure 6). Winter and spring maximum temperature anomalies, however, were notably more positive, signifying the expected increase in maximum temperatures due to global warming. It is worth noting, however, that the unexpected decrease in maximum temperatures are also present in the fall, which could be evidence against the hypothesis. However, this paper is only focused on the summer temperature anomalies. The mean and median minimum temperature anomalies show an increase in temperatures across all seasons, consistent with the expectation from global warming. Minimum temperatures during the summer season are not expected to show a negative trend, as evapotranspiration peaks during the middle of the day, when maximum temperatures are generally observed, rather than the night or dawn, when minimum temperatures are generally observed. Additional temperature anomaly plots at a finer decadal, county-level resolution beyond the corn belt states are provided in the Appendix A. We emphasize that by subtracting the mean maximum temperature for each day of the year and temperature grid, much of the seasonal and location variability that are observed long-term are removed. Utilizing these anomalies avoid possibly misleading trends from seasonality and location variation.

Figure 6

Mean and Median of Maximum or Minimum Temperature Anomalies for the Corn Belt States per Season, 1981–2019



Note. Shading of each state represents higher (red) or lower (blue) temperature anomalies. Share of land within each state devoted to corn or soy cultivation is represented by the size of the indigo circle within each state. The value of crop share was calculated as an average of crop share in 2010–2019, and is consistent across panels.

2.5 Regression methodology

We aim to estimate the maximum temperature anomaly using dummy variables for each "corn peak week" ($cpwk$) and "soybean peak week" ($spwk$) interacted with the respective crop areas while accounting for location, year, and week of the year. As previously mentioned, $cpwk_k$ dummy variables range from $cpwk_{-10}$ to $cpwk_{+10}$, spanning 21 "weeks", or 147 days of the year, where the $cpwk_k$ dummy variables as $k \rightarrow 0$ are expected to have a more negative effect on temperature anomalies. $spwk_j$ dummy variables are expected to behave in a similar way. By using independent variables that were not determined by overarching trends along the timeline, we can attempt to separate the effects of corn and soybean cultivation from the year-to-year trends. There are, however, significant limitations to this model, which will be discussed later.

The regression is:

$$y_{it} = \sum_{k=-10}^{10} \beta_k \left(cpwk_k * A_i^c\right) + \sum_{j=-10}^{10} \beta_j \left(spwk_j * A_i^s\right) + s_{lat}(lat_i) * s_{long}(long_i)$$

$$* \, s_{year}(year) * s_{woy}(woy)$$

where

A_i^c is the average corn cultivation area to total state area ratio

A_i^s is the average soybean cultivation area to total state area ratio

k is the number of the "week" defined by corn peak week and $-10 \leq k \leq 10$

j is the number of the "week" defined by soy peak week and $-10 \leq j \leq 10$

$s_{lat}(lat_i)$ is a spline of the latitude associated with the state, where degrees of freedom (df) = 3

$s_{long}(long_i)$ is a spline of the latitude associated with the state, where df = 2

$s_{year}(year)$ is a spline of the year, where df = 3

$s_{woy}(woy)$ is a spline of the week of the year, where df = 3

and y_{it} is the daily maximum temperature anomaly in °C for the state which was calculated by averaging the daily maximum temperature anomaly of grids that had more than 1% of the total area devoted to corn and soybean cultivation. The pre-sorting of temperature grids allows us to see the true impact of crop by focusing only on areas that would be affected by crop, minimizing the effects of dilution due to aggregation of weather at the state level.

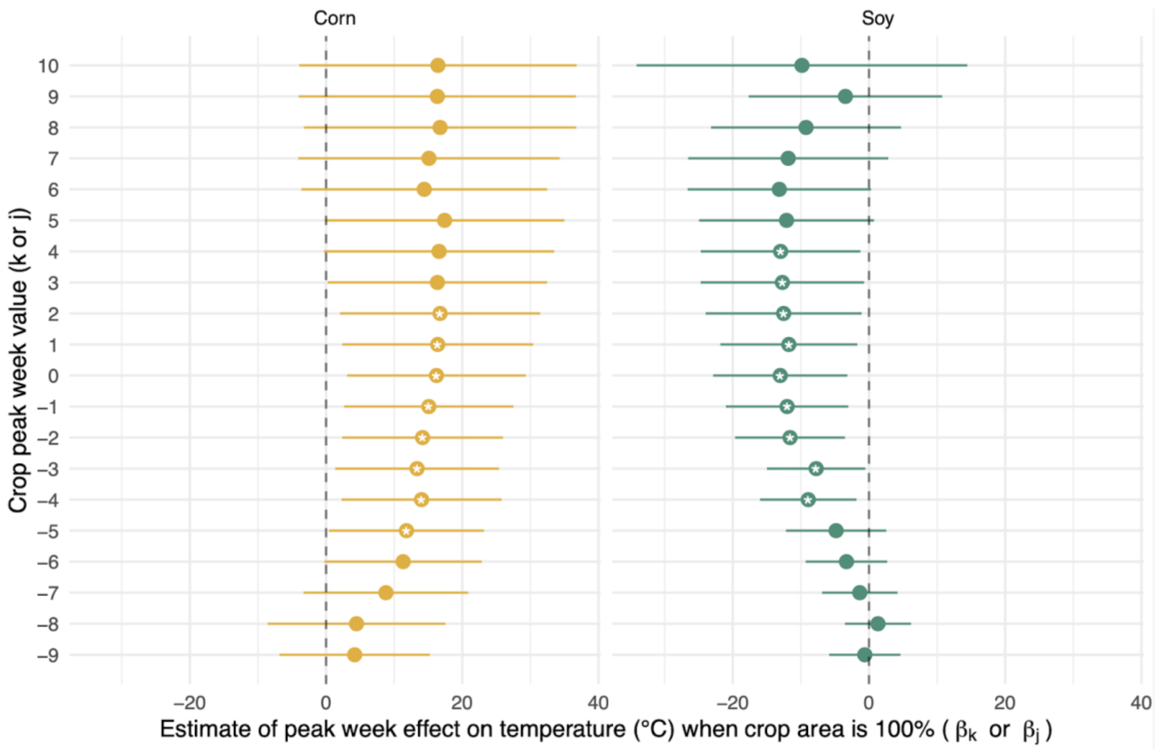
3.0 RESULTS

The regression gives mixed results. A summation of the coefficient of the peak week variable ($cpwk_k$ or $spwk_j$) with its interaction with the crop area variable (A_i^c or A_i^s) can be interpreted as the effect of that crop peak week given that state's crop area is equal to the total state area, or, in variable terms, β_k at A_i^c = 1 or β_j at A_i^s = 1 for corn and soy, respectively. $cpwk_{-10}$ to $spwk_{-10}$ are used as reference dummy variables (when all other $cpwk_k$ or $spwk_j$ variables are 0) within the regression. Standard errors were clustered according to years, using the vcovCL method from the sandwich package in R. The summation was manually calculated after the regression produced individual coefficient results for each dummy variable and interaction, and the standard errors were manually calculated using the covariance matrix generated from the clustered standard error function. Using clustered standard errors noticeably decreases the significance of all coefficients, however, is a robust method of evaluating the coefficients.

Looking at this coefficient summation value, we see positive values for the corn peak weeks, with the values seemingly greater near k = 0, which was opposite of the effect we thought we would see. The summation of coefficients for the soybean peak weeks, however, are negative, with slightly more negative values surrounding j = 0 (Figure 7). This is very surprising, as literature would suggest that corn has a greater evapotranspiration rate than soybean. It is worth noting that the summation of coefficients for the soybean peak week variables are more significant than that of the corn peak week variables, as seen in the slightly smaller standard errors (Appendix B). The fit of the regression was conventionally low, with an R^2 of 0.047 (0.042 adj.).

Figure 7

Plot of Summed Coefficients from Regression Analysis

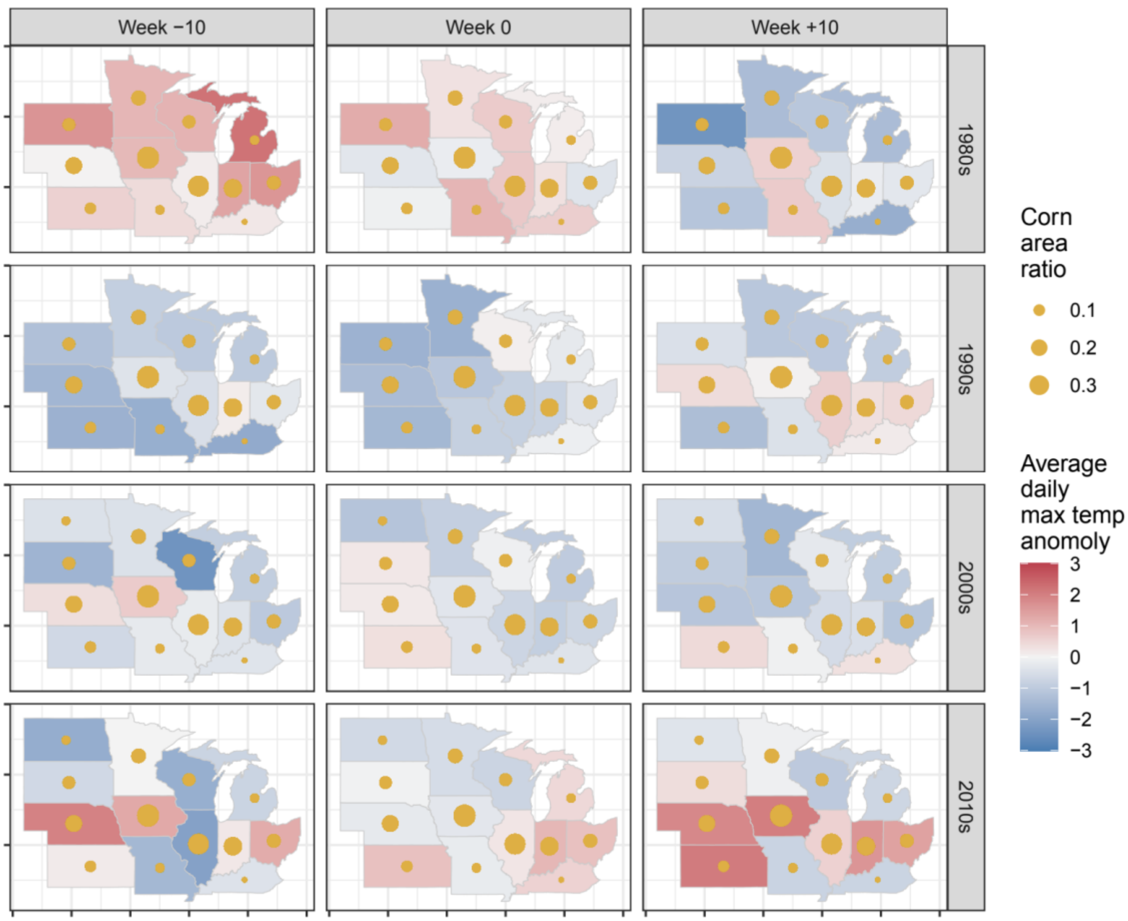


Note. The main effect of each corn or soy peak week value is added to the interaction effect between the crop peak week and its respective share of area. Values can be interpreted as the effect of that peak week value (where peak week 0 is the week with the highest levels of evapotranspiration) when the crop area is equal to the entire state's area. Table with standard errors and significance is provided in Appendix B. Negative values (which are observed in the coefficients of soybean variables $spwk_j + spwk_j * A_i^s$) would mean that there is a cooling effect, while positive values (which are observed in the coefficients of corn variables $cpwk_k + cpwk_k * A_i^c$) mean that there is a heating effect.

We see similar results visually when comparing the average temperature anomalies for $cpwk_k$ (Figure 8) or $spwk_j$ (Figure 9) for k or j values of -10, 0, and 10. Cooling is not evident in $cpwk_0$ and values are in fact comparable to $cpwk_{10}$. Cooling is more evident across all $spwk_k$ panels, with $cpwk_0$ values seemingly comparable to $cpwk_{10}$ values. However, the regression coefficient results above include interactions with the crop area. We can see in Figure 9 that some of the states with larger soybean crop area actually display a negative temperature anomaly in $spwk_{10}$for the 2000s and 2010s decades. We also see a noticeable warmer 1980s decade across all weeks in both Figure 8 and Figure 9, which is also present in the seasonal decadal temperature anomaly maps for spring and summer in the appendix. There is not much literature on why we observe these values, but it is worth noting that there were major droughts in 1983 and 1988 in the Midwest in addition to a 1980 heatwave in central North America. As mentioned, there is a noticeable variation among warming hole literature on different ways to calculate temperature anomaly or temperature trends.

Figure 8

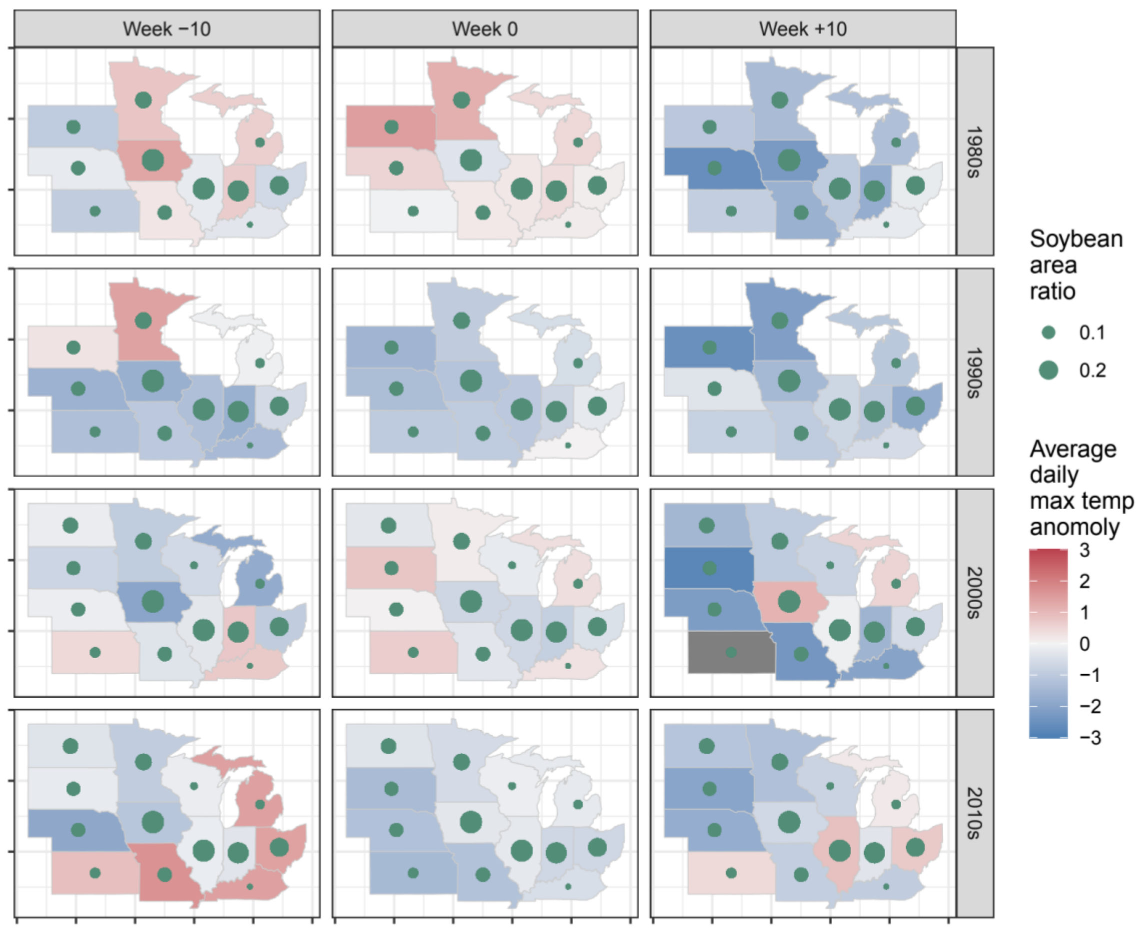
Average Daily Maximum Temperature Anomaly for Each State Within the Corn Belt Region According to Corn Peak Week Number ($\boldsymbol{cpwk}_{-10}$, $\boldsymbol{cpwk}_{0}$, and $\boldsymbol{cpwk}_{10}$) and Decade for the Study Period 1981–2019



Note. The darkest blue color represents a cooler temperature anomaly while the darkest red color represents a warmer temperature anomaly. Corn area ratio relative to the total area of the state is also shown. The timing of the $cpwk$ varies by state and year.

Figure 9

Average Daily Maximum Temperature Anomaly for Each State Within the Corn Belt Region According to Soybean Peak Week Number ($spwk_{-10}$, $spwk_0$, and $spwk_{10}$) and Decade for the Study Period 1981–2019



Note. The darkest blue color represents a cooler temperature anomaly while the darkest red color represents a warmer temperature anomaly. The temperature anomalies and soybean area ratio relative to the total state area are shown. Kansas temperature anomaly in Week +10 during the 2000s decade is greyed out, as it's average temperature anomaly is very negative, at -4.3. We excluded the state's temperature data from the visualization to maintain consistent scaling of the color bar to be compared with Figure 8. The timing of the $spwk$ varies by state and year.

4.0 DISCUSSION

The results from this paper are quite unexpected and do not provide strong evidence in support of the hypothesis that agricultural production contributes to the warming hole. We observe a cooling effect of soybean on maximum temperatures surrounding its peak evapotranspiration period, and even a slight cooling effect further away from its peak evapotranspiration period. However, the results are completely opposite of the effect of the peak evapotranspiration times of corn. This is very contrary to findings in existing literature, which would expect similar, if not more, cooling from corn, due to a slightly greater rate of evapotranspiration. Additionally, the analysis of temperature data does not define the warming hole as clearly as some other papers have claimed.

We attempted to use simple definitions and analysis to generate easily interpretable results while avoiding a broad trend analysis, so there are some limitations of the model. Firstly, the definition of the peak week is based on available USDA data, which is limited to a cumulative count of crop progress at the state level spanning back to 1981 at the earliest. When the cumulative count reaches the 50%, the batch of crop planted at the earliest time period may have already passed the time peak evapotranspiration period. Additionally, the net amounts of crop within the peak evapotranspiration period slightly vary among years and states. There is no standard rate of planting observed in the states, growth rates are dependent on temperatures of the season, and extremely limited data is available for the next significant growth stages, all making it difficult to obtain an accurate count of crop at peak evapotranspiration. We do achieve some level of mitigation to this issue through the use of dummy variables. The use of dummy variables spanning a wider time period without assuming a linear relationship between the "peak weeks" gave us an opportunity to compare the effects of the time periods generally surrounding the defined "peak week 0" to time periods further away (when temperatures are likely to be unaffected by a majority of crop cultivation).

The fit of the model was poor under the conventional measurement of fit, R^2, at around 0.04. This means that our model only explains about 4% of the temperature anomaly variance. However, we were not expecting the fit of our model to be exceptionally great because from literature, it is clear that the warming hole is a byproduct of multiple factors. Additionally, the dependent variable has already removed concerns of seasonality and variability from location. The regression includes the spline interactions of years and week of years, so it is possible that some effects from cyclic patterns could be picked up within the regression. However, further analysis on specific oscillations is required to solidify this claim.

Some of the effects, particularly from the soybean "peak week" dummy variables are statistically significant ($p < 0.05$) even with clustered standard errors. The negative values for nearly all soybean peak week dummy variables (even those further from peak week 0), suggests that there might be much larger factors at play, possibly including a factor that affects early and late summer season weather differently, as soybean is typically planted later than corn. There are a few years where some states' $cpwk_0$and $spwk_0$ occur in the same or similar week of the year, causing possible multicollinearity issues (Appendix C). However, regressions run with corn and soy variables independently using the same dataset display the same pattern that $spwk_j + spwk_j * A_i^s$ is coefficients are more negative than that of corn (Appendix B).

The trends of precipitation across the years are very clearly increasing in nearly all states (Figure 3). Regression results analyzing precipitation anomalies against the peak week variables show more negative values for $cpwk_k$ and more positive values for $spwk_j$, nearly opposite of the regression results against a dependent variable of maximum temperature anomaly values (Appendix D). This leads us to wonder about the possibility of the involvement of precipitation or other weather variables on the main regression. On a related note, excessive rain may delay corn and soybean planting times, hence, early season weather may affect my independent variables (Braun, 2019; Robbins, 1978). However, this is not the case of omitted variable bias as precipitation anomalies weeks ahead of time is not likely a predictor of maximum temperature anomalies. It may be possible for weather systems which affect precipitation and maximum temperatures weeks (or longer) at a time. These weather systems include jet streams, ocean-atmosphere oscillations, and fronts or cyclones, which are not accounted for in the model.

There is also some literature on the effects on agricultural practices on albedo, or reflection of short wave radiation, which gives a cooling effect. Davin et al. (2014) explored differences in cooling from albedo and evapotranspiration based on tilling practices and found that the no-till practice potentially provided local cooling. Under this understanding of agricultural impact on climate, rather than strictly evapotranspiration during the growth season, the effects of agriculture on climate are potentially more complicated than what we accounted for in our model. It is worth noting, however, that the no-till practice is not yet widely adopted and hence, its cooling effects in the midwestern warming hole region may not be of significance (Huggins & Reganold, 2008).

5.0 CONCLUSION

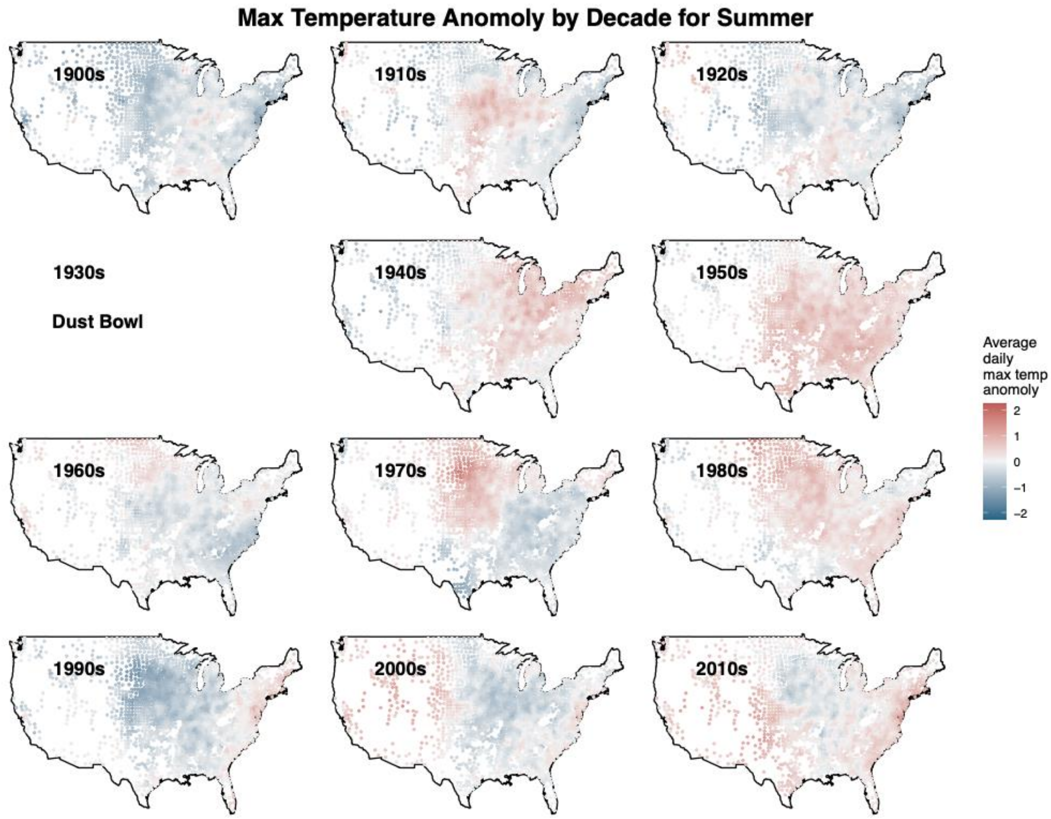
The direct impact of corn and soybean cultivation on the warming hole are not the same, according to our results. Our study attempted to identify the temperature anomalies during the summertime for the Midwestern warming hole region using the expected period of maximum evapotranspiration from corn or soybean. Corn production was found to have a positive impact on temperatures, while soybean production was found to have a negative impact, which is an observation largely unexplainable by literature. Additionally, soybean production has increased at a greater rate than corn in more recent years, suggesting that the increasing soybean production contributed to the warming hole. However, we were unable to find a plausible explanation from existing literature on the mechanism by which this occurs. These results do not support the hypothesis that agricultural intensification enforces the warming hole via the process of evapotranspiration.

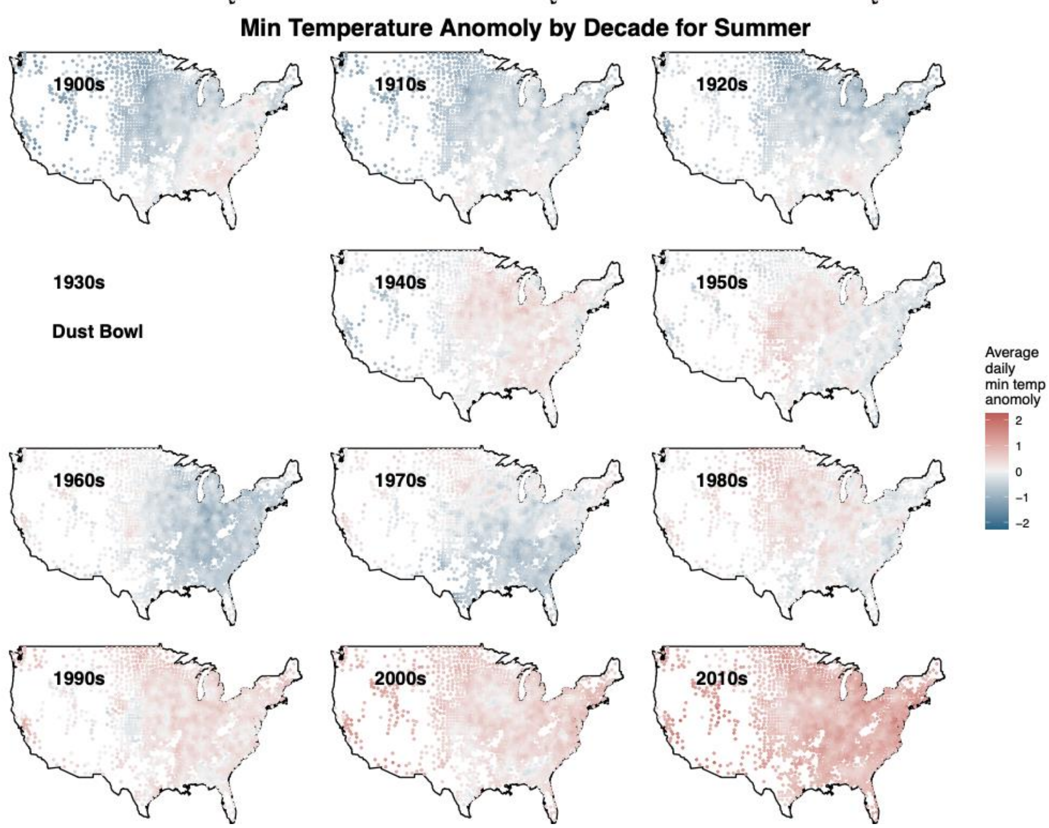
Our regression, which measured the effect of corn and soybean theoretical peak evapotranspiration periods within the state and accounted for interacting location, between-year, and between-week trends, explained 4% of maximum temperature anomaly variance. As the maximum temperature anomaly is mean-centered based on grid and day of the year observation, seasonality and location variation observed long-term are removed from the regression. Under this understanding, the fit of the model is not unexpectedly low.

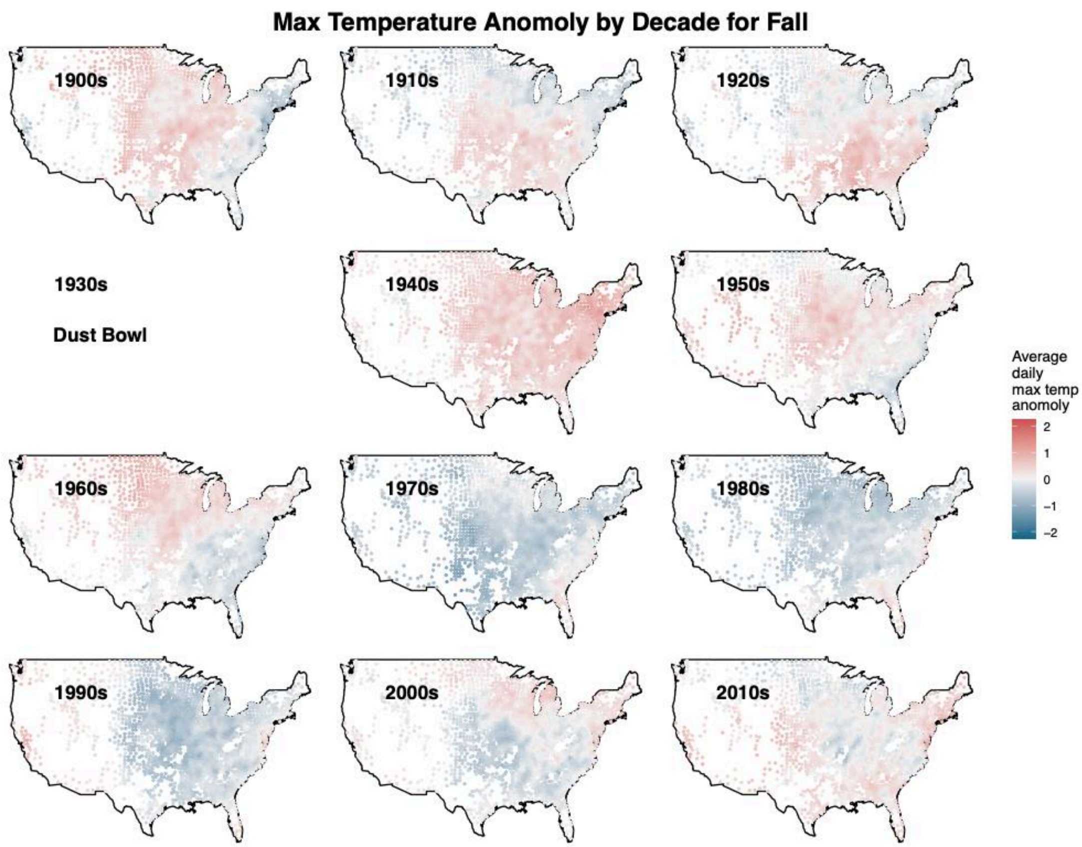
Some correlations between soybean at peak evapotranspiration periods and maximum temperature anomalies were found to be significant ($p < 0.05$) even with more robust standard errors clustered by year, which calls for further research and exploration. Corn peak evapotranspiration periods were found to be generally slightly less significant. It is possible that factors affecting maximum temperatures differently in early versus later summer seasons could explain the results reasonably. Additionally, these other factors could affect evapotranspiration rates differently. Hence, the effect of crop evapotranspiration could vary from our results with an addition of other interacting factors.

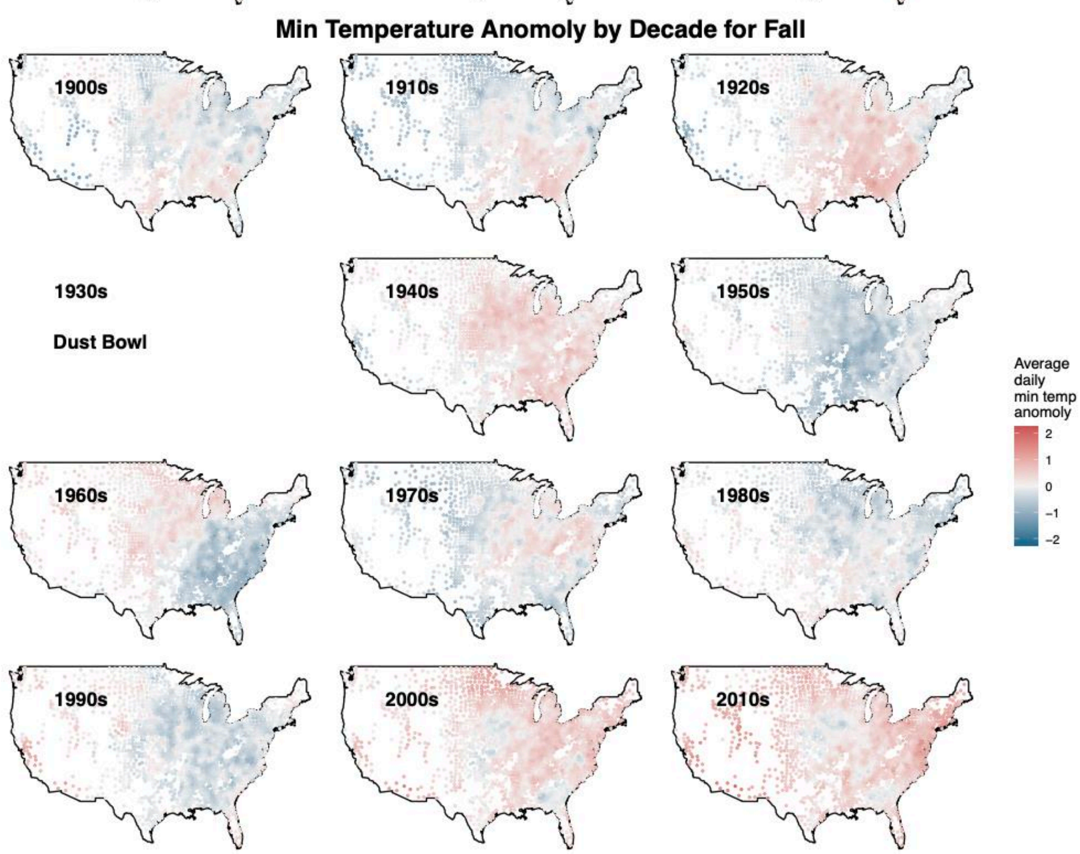
As an initial run to relate crop intensification evapotranspiration and temperature cooling independently of general linear trends, the results were large, unexpected, and statistically significant for some effects. There are other possible ways that crop cultivation could encourage the warming hole other than evapotranspiration, such as extreme-heat cooling from albedo of non-tilled fields, as Davin et al. (2014) suggested. These preliminary results show the warming hole is likely a result of many factors aligning and interacting, beyond crop evapotranspiration. Further exploration of other warming hole effects and their potential interaction with agriculture might be required to obtain a succinct explanation of the results.

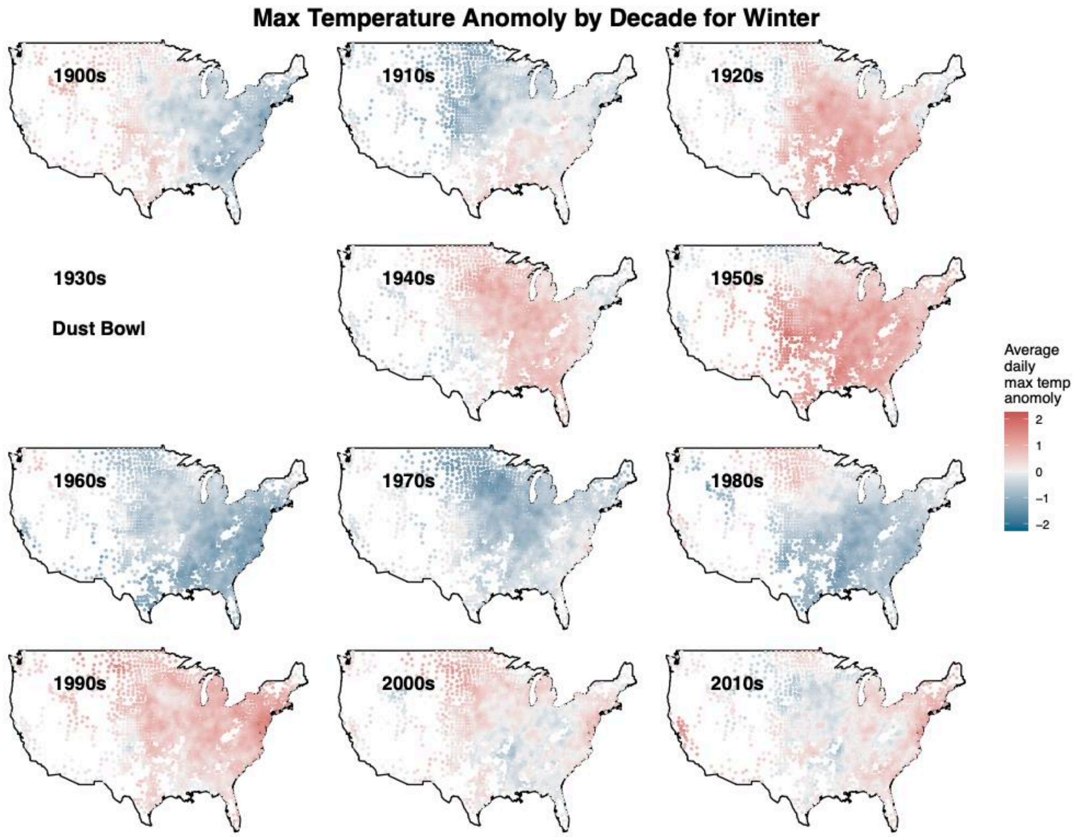
APPENDIX A Weather Anomaly Maps by Season and Decade

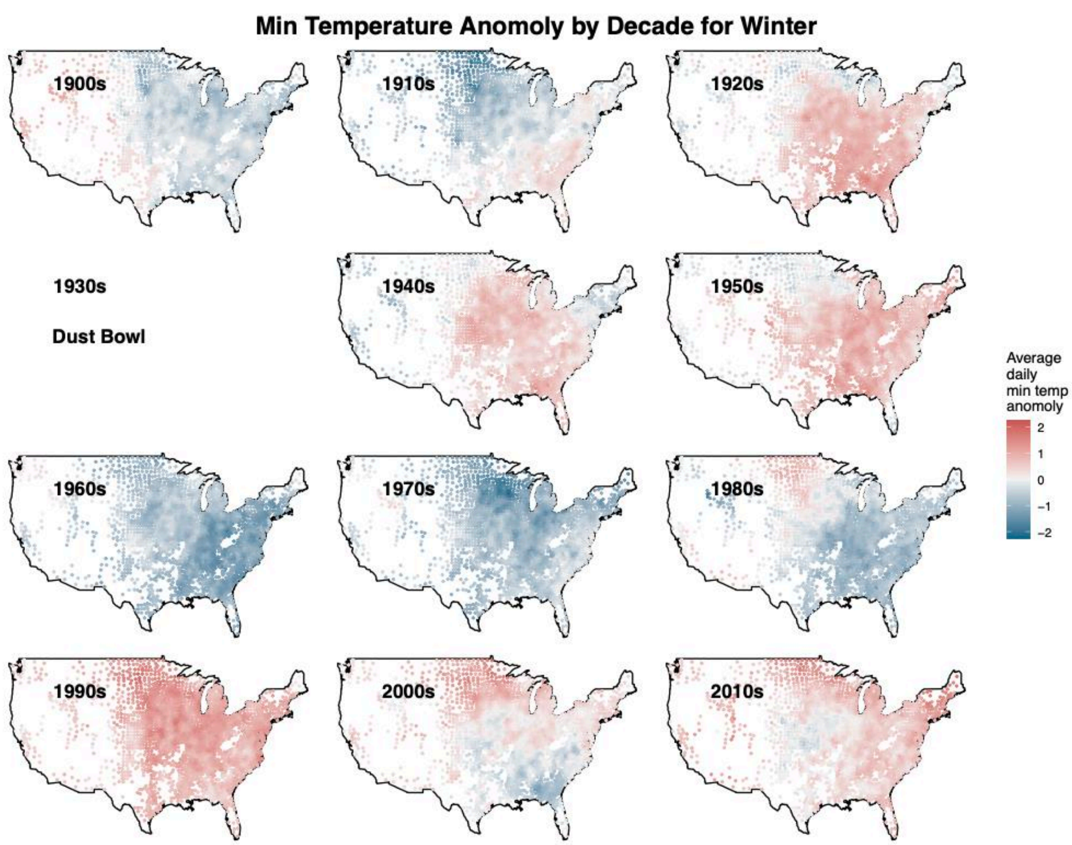


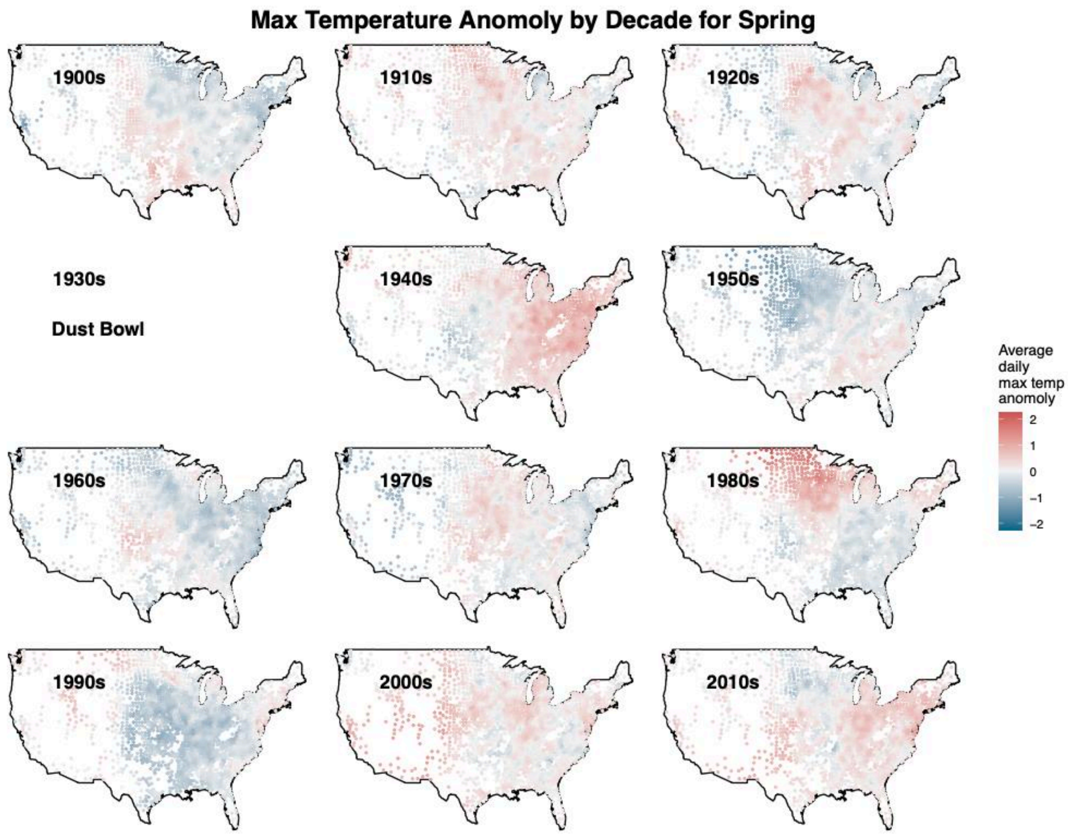


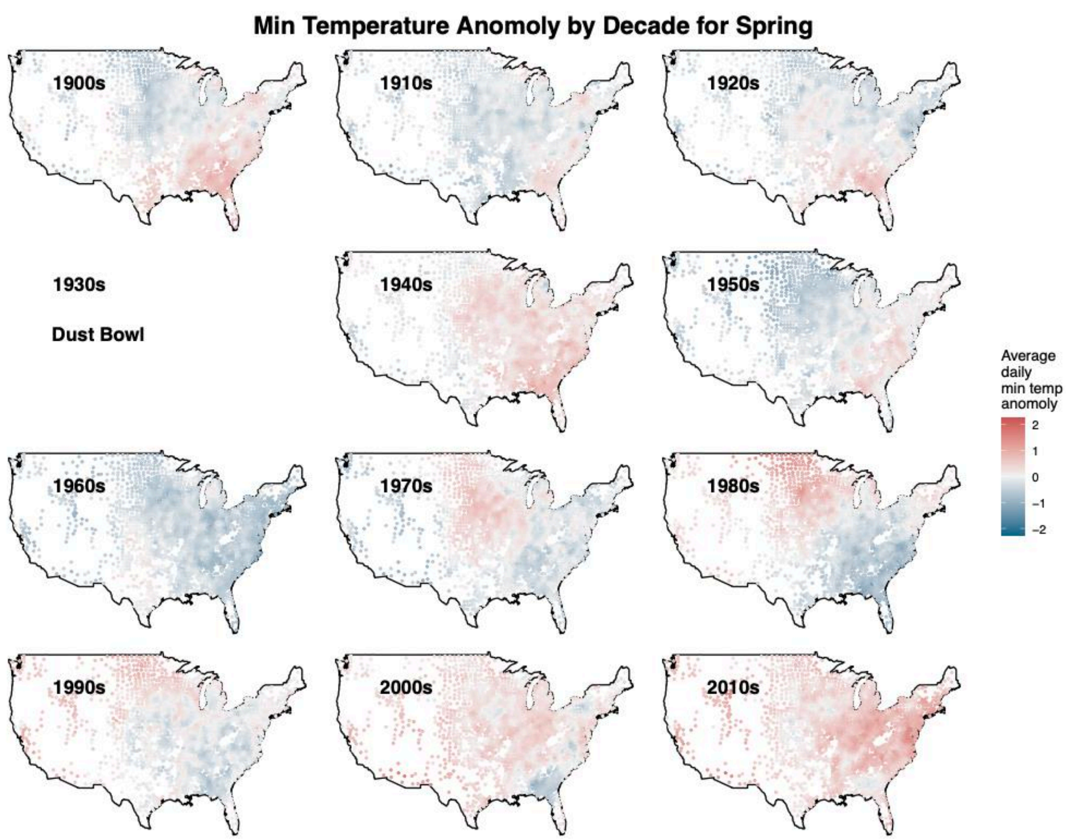

Max Temperature Anomoly by Decade for Fall
1900s
1910s
1920s
1930s
Dust Bowl
1940s
1950s
1960s
1970s
1980s
1990s
2000s
2010s
Average daily max temp anomoly
2
1
0
−1
−2

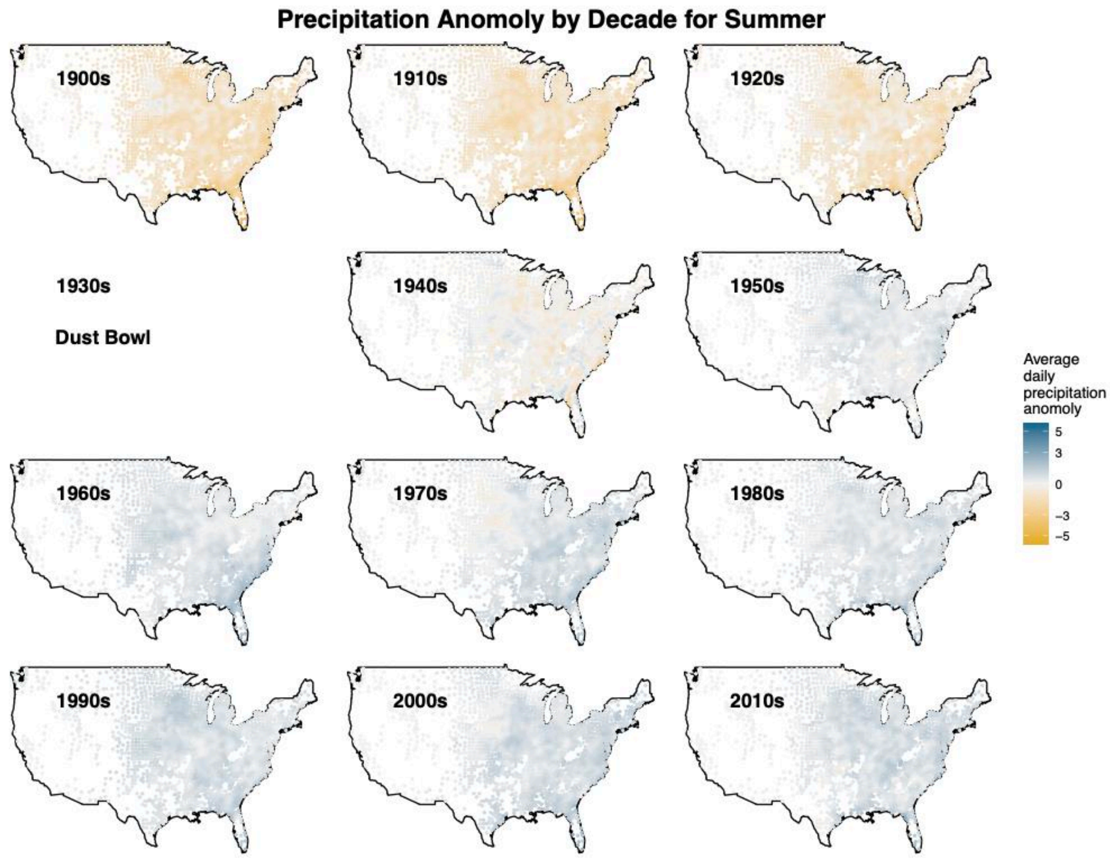

Min Temperature Anomoly by Decade for Fall
1900s
1910s
1920s
1930s
Dust Bowl
1940s
1950s
1960s
1970s
1980s
1990s
2000s
2010s
Average daily min temp anomoly
2
1
0
−1
−2

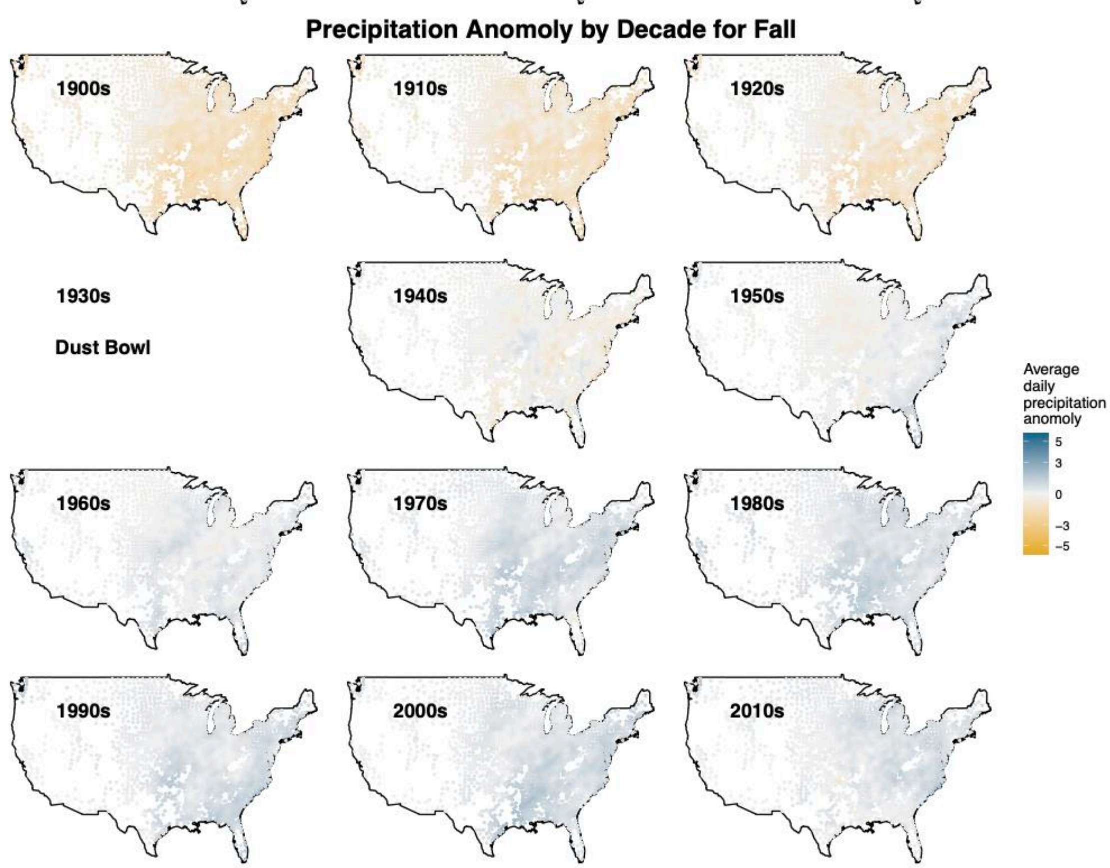

Max Temperature Anomoly by Decade for Winter
1900s
1910s
1920s
1930s
Dust Bowl
1940s
1950s
1960s
1970s
1980s
1990s
2000s
2010s
Average daily max temp anomoly
2
1
0
−1
−2


Min Temperature Anomoly by Decade for Winter
1900s
1910s
1920s
1930s
Dust Bowl
1940s
1950s
1960s
1970s
1980s
1990s
2000s
2010s
Average daily min temp anomoly
2
1
0
−1
−2

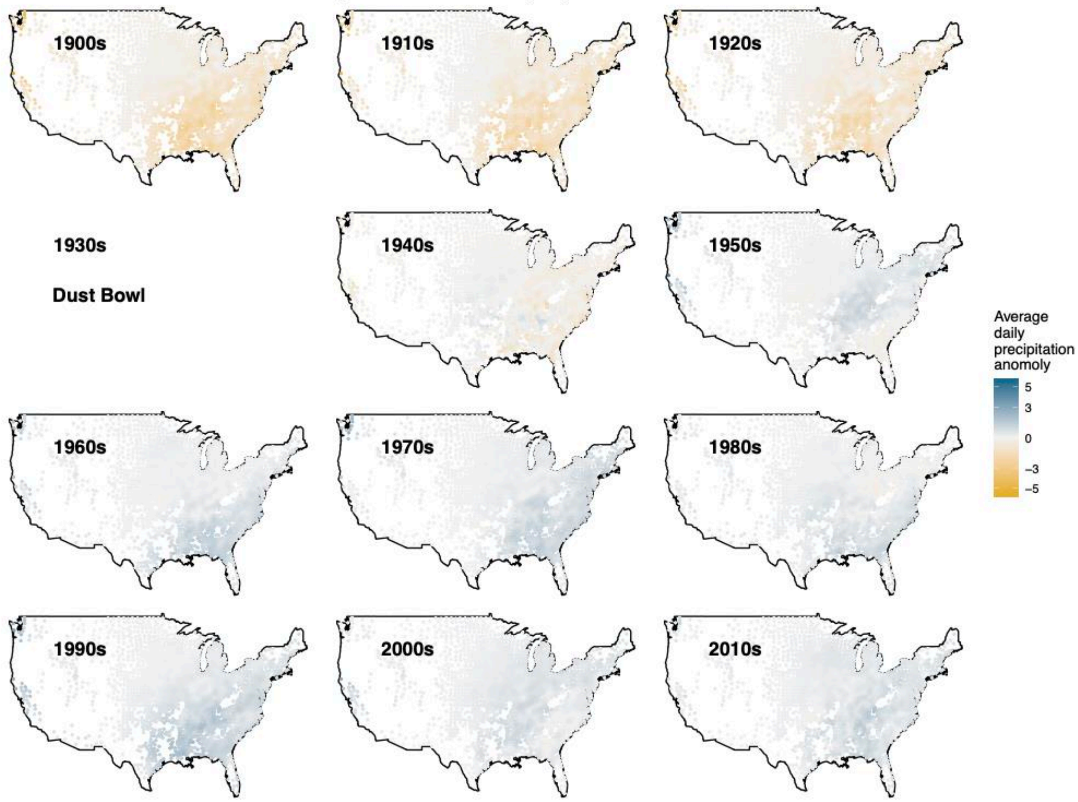

Max Temperature Anomoly by Decade for Spring
1900s
1910s
1920s
1930s
Dust Bowl
1940s
1950s
1960s
1970s
1980s
1990s
2000s
2010s
Average daily max temp anomoly
2
1
0
−1
−2


Min Temperature Anomoly by Decade for Spring
1900s
1910s
1920s
1930s
Dust Bowl
1940s
1950s
1960s
1970s
1980s
1990s
2000s
2010s
Average daily min temp anomoly
2
1
0
−1
−2

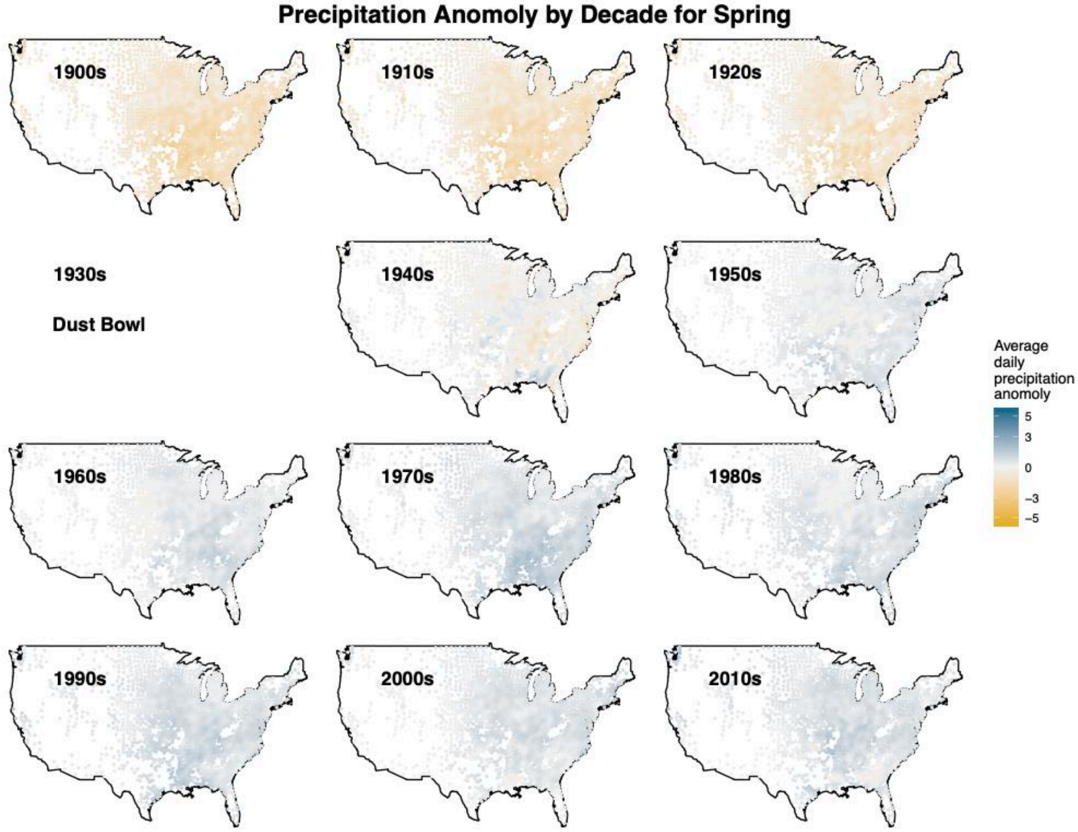

Precipitation Anomoly by Decade for Summer
1900s
1910s
1920s
1930s
Dust Bowl
1940s
1950s
1960s
1970s
1980s
1990s
2000s
2010s
Average daily precipitation anomoly
5
3
0
−3
−5


Precipitation Anomoly by Decade for Fall
1900s
1910s
1920s
1930s
Dust Bowl
1940s
1950s
1960s
1970s
1980s
1990s
2000s
2010s
Average daily precipitation anomoly
5
3
0
−3
−5

Precipitation Anomoly by Decade for Winter



Precipitation Anomoly by Decade for Spring



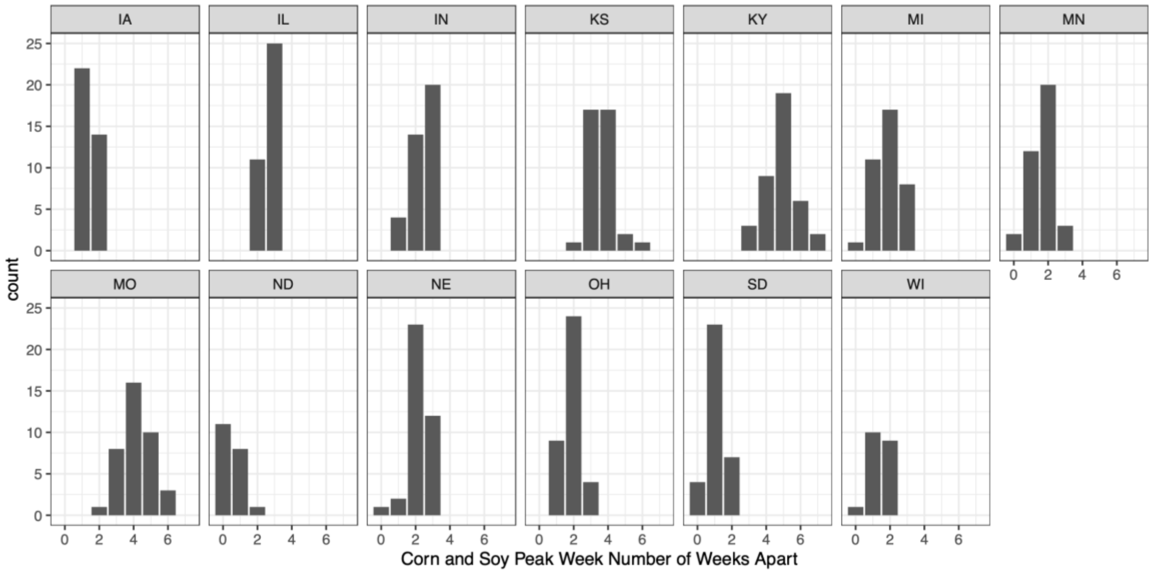
APPENDIX B Table of Summed Coefficients from Regression

	Corn Only	Soy Only	Corn & Soy
C(-9) + C(-9):cA	0.50 (1.82)		4.20 (5.64)
C(-8) + C(-8):cA	-0.88 (1.80)		4.47 (6.65)
C(-7) + C(-7):cA	4.88 (2.04)*		8.79 (6.17)
C(-6) + C(-6):cA	6.52 (2.26)**		11.31 (5.89)
C(-5) + C(-5):cA	6.65 (2.03)**		11.80 (5.80)*
C(-4) + C(-4):cA	8.49 (2.40)**		14.02 (5.99)*
C(-3) + C(-3):cA	6.70 (2.81)*		13.36 (6.13)*
C(-2) + C(-2):cA	6.72 (2.61)*		14.17 (6.02)*
C(-1) + C(-1):cA	6.97 (3.05)*		15.09 (6.34)*
C(0) + C(0):cA	7.50 (3.26)*		16.21 (6.69)*
C(1) + C(1):cA	6.74 (3.54)		16.40 (7.15)*
C(2) + C(2):cA	6.98 (3.96)		16.74 (7.50)*
C(3) + C(3):cA	6.75 (4.38)		16.35 (8.22)
C(4) + C(4):cA	6.92 (4.87)		16.59 (8.62)
C(5) + C(5):cA	7.19 (5.25)		17.40 (8.96)
C(6) + C(6):cA	3.99 (4.97)		14.41 (9.21)
C(7) + C(7):cA	5.10 (5.50)		15.11 (9.79)
C(8) + C(8):cA	7.61 (5.99)		16.74 (10.20)
C(9) + C(9):cA	8.26 (6.19)		16.34 (10.38)
C(10) + C(10):cA	10.26 (6.24)		16.43 (10.39)
S(-9) + S(-9):sA		3.19 (2.45)	-0.62 (2.67)
S(-8) + S(-8):sA		7.72 (2.46)**	1.32 (2.48)
S(-7) + S(-7):sA		6.51 (2.59)*	-1.35 (2.83)
S(-6) + S(-6):sA		5.42 (2.90)	-3.31 (3.05)
S(-5) + S(-5):sA		4.45 (3.33)	-4.83 (3.76)
S(-4) + S(-4):sA		0.55 (2.93)	-8.92 (3.61)*
S(-3) + S(-3):sA		2.72 (3.26)	-7.75 (3.69)*
S(-2) + S(-2):sA		-0.24 (3.54)	-11.59 (4.12)**
S(-1) + S(-1):sA		-0.13 (3.67)	-12.02 (4.59)*
S(0) + S(0):sA		-1.36 (4.23)	-13.03 (5.03)*
S(1) + S(1):sA		-0.41 (4.72)	-11.77 (5.13)*
S(2) + S(2):sA		-0.79 (5.32)	-12.53 (5.84)*
S(3) + S(3):sA		-0.84 (5.65)	-12.72 (6.12)*
S(4) + S(4):sA		-1.51 (5.47)	-12.98 (5.98)*
S(5) + S(5):sA		-0.25 (5.72)	-12.11 (6.55)
S(6) + S(6):sA		-0.53 (6.21)	-13.16 (6.87)
S(7) + S(7):sA		0.87 (6.41)	-11.86 (7.50)
S(8) + S(8):sA		4.48 (6.36)	-9.24 (7.12)
S(9) + S(9):sA		5.28 (6.46)	-3.46 (7.25)
S(10) + S(10):sA		4.57 (7.00)	-9.84 (12.39)
r.squared	0.05	0.04	0.05
adj.r.squared	0.04	0.03	0.04
AIC	354377.99	356868.54	310478.36
BIC	356942.84	359433.39	313367.87
logLik	-176906.99	-178152.27	-154917.18

***$p < 0.001$; **$p < 0.01$; *$p < 0.05$

Note. $cpwk_k$ or $spwk_j$ coefficient is summed with its interaction with crop share relative to the state, A_i^c or A_i^s , respectively. Coefficients can be interpreted as the effect of peak week k or j when share of corn or soybean relative to total state area is equal to 1. In the observed data, A_i^c ranges from 0.05 to 0.37, while A_i^s ranges from 0.05 to 0.26. Regressions run with only corn or soy as regressors using the same dataset are also shown for comparison. Standard errors are clustered by years.

APPENDIX C Count of difference in week of the year between $\boldsymbol{cpwk_0}$ or $\boldsymbol{spwk_0}$



Note. The week of the year at which k = 0 in $cpwk_k$ was subtracted from the week of the year at which j = 0 in $spwk_j$ for each available year in each state. The bar graphs show the distribution of these differences for each state.

APPENDIX D Table of Summed Coefficients from Regression on Temperature and Precipitation Anomalies

	Temp Max	Temp Min	Precipitation
C(-9) + C(-9):cA	4.20 (5.64)	2.96 (4.22)	-14.70 (12.99)
C(-8) + C(-8):cA	4.47 (6.65)	1.08 (4.75)	-18.18 (12.36)
C(-7) + C(-7):cA	8.79 (6.17)	3.68 (4.41)	-20.02 (12.25)
C(-6) + C(-6):cA	11.31 (5.89)	5.65 (4.47)	-21.85 (11.82)
C(-5) + C(-5):cA	11.80 (5.80)*	5.62 (4.34)	-22.95 (11.54)
C(-4) + C(-4):cA	14.02 (5.99)*	7.28 (4.49)	-25.30 (11.35)*
C(-3) + C(-3):cA	13.36 (6.13)*	7.08 (4.79)	-24.65 (11.40)*
C(-2) + C(-2):cA	14.17 (6.02)*	7.04 (4.58)	-26.40 (11.45)*
C(-1) + C(-1):cA	15.09 (6.34)*	7.85 (4.73)	-25.79 (11.77)*
C(0) + C(0):cA	16.21 (6.69)*	8.77 (4.97)	-26.05 (11.76)*
C(1) + C(1):cA	16.40 (7.15)*	9.09 (5.23)	-24.52 (11.89)*
C(2) + C(2):cA	16.74 (7.50)*	8.98 (5.42)	-24.63 (12.36)
C(3) + C(3):cA	16.35 (8.22)	10.23 (5.62)	-22.12 (12.40)
C(4) + C(4):cA	16.59 (8.62)	10.23 (5.72)	-21.15 (13.00)
C(5) + C(5):cA	17.40 (8.96)	10.89 (5.79)	-21.42 (13.08)
C(6) + C(6):cA	14.41 (9.21)	8.39 (5.89)	-20.48 (13.35)
C(7) + C(7):cA	15.11 (9.79)	9.03 (5.70)	-19.89 (13.44)
C(8) + C(8):cA	16.74 (10.20)	10.42 (6.05)	-19.15 (14.01)
C(9) + C(9):cA	16.34 (10.38)	10.40 (5.84)	-15.73 (13.41)
C(10) + C(10):cA	16.43 (10.39)	10.43 (6.06)	-16.40 (13.37)
S(-9) + S(-9):sA	-0.62 (2.67)	1.26 (2.11)	1.88 (2.60)
S(-8) + S(-8):sA	1.32 (2.48)	2.68 (2.04)	4.39 (3.28)
S(-7) + S(-7):sA	-1.35 (2.83)	0.14 (2.32)	7.10 (3.29)*
S(-6) + S(-6):sA	-3.31 (3.05)	-1.10 (2.83)	9.29 (4.14)*
S(-5) + S(-5):sA	-4.83 (3.76)	-1.81 (3.53)	11.49 (4.34)*
S(-4) + S(-4):sA	-8.92 (3.61)*	-5.35 (3.23)	10.05 (3.90)*
S(-3) + S(-3):sA	-7.75 (3.69)*	-3.47 (3.30)	11.34 (4.49)*
S(-2) + S(-2):sA	-11.59 (4.12)**	-6.75 (3.67)	8.37 (4.81)
S(-1) + S(-1):sA	-12.02 (4.59)*	-8.41 (4.10)*	7.87 (4.82)
S(0) + S(0):sA	-13.03 (5.03)*	-9.65 (4.48)*	5.82 (5.11)
S(1) + S(1):sA	-11.77 (5.13)*	-9.38 (4.49)*	4.76 (5.25)
S(2) + S(2):sA	-12.53 (5.84)*	-11.50 (5.07)*	3.04 (5.08)
S(3) + S(3):sA	-12.72 (6.12)*	-10.59 (5.35)	4.48 (5.58)
S(4) + S(4):sA	-12.98 (5.98)*	-10.07 (5.07)	5.98 (5.42)
S(5) + S(5):sA	-12.11 (6.55)	-11.21 (5.42)*	2.95 (5.25)
S(6) + S(6):sA	-13.16 (6.87)	-11.53 (5.69)*	4.32 (5.98)
S(7) + S(7):sA	-11.86 (7.50)	-14.29 (6.21)*	-0.05 (6.22)
S(8) + S(8):sA	-9.24 (7.12)	-11.51 (6.97)	-0.15 (6.33)
S(9) + S(9):sA	-3.46 (7.25)	-9.50 (6.97)	-1.05 (6.78)
S(10) + S(10):sA	-9.84 (12.39)	-19.95 (12.89)	-0.32 (11.65)
r.squared	0.05	0.05	0.01
adj.r.squared	0.04	0.04	0.01
AIC	310478.36	298624.19	341925.97
BIC	313367.87	301513.70	344815.47
logLik	-154917.18	-148990.10	-170640.98

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$

Note. $cpwk_k$ or $spwk_j$ coefficient is summed with its interaction with crop share relative to the state, A_i^c or A_i^s , respectively. Coefficients can be interpreted as the effect of peak week k or j when share of corn or soybean relative to total state area is equal to 1. In the observed data, A_i^c ranges from 0.05 to 0.37, while A_i^s ranges from 0.05 to 0.26. Regressions are run against daily maximum temperature anomalies, daily minimum temperature anomalies, and daily precipitation anomalies. Standard errors are clustered by years.

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